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CHARACTERISTICS AND POLLUTION PROBLEMS OF IRRIGATION RETURN FLOW

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CHARACTERISTICS AND POLLUTION PROBLEMS
OF
IRRIGATION RETURN FLOW

Prepared by

UTAH STATE UNIVERSITY FOUNDATION

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27 Abstract
An extensive review of the literature was made to assess the present state of scientific knowledge and technology regarding water pollution problems associated with the practice of irrigation and occurring in irrigation return flow. Literature dealing specifically with irrigation return flow was sparce. Eighty percent of the irrigated area of the U.S. was found to fall within an area in which the water demands exceed or will exceed the supply by 1980. Water quality changes during irrigation were found to be influenced by: (a) biochemical action, (b) erosion, (c) evaporation and transpiration, (d) filtration, (e) heat transfer, (f) ion exchange, (g) leaching, (h) precipitation, and (i) sorption and chelation. The effect of irrigation on the subsequent reuse of water by other users was considered. Feasibility studies have been conducted on treating and disposing of return water. A need was found for economic research explicitly concerned with irrigation return flow. The legal aspects of reuse and water quality of irrigation return flows were examined and the recommendation made for more intensive study of the inseparable nature of quality-quantity management in relation to institutional, economic, and legal restrictions. This article contains 245 references and a separate bibliography of 700 entries.

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Abstractor	Institution
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In preparation of the report, extensive use has been made of pertinent literature, and a conscientious effort has been made to cite all source material.

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SUMMARY GENERALIZATIONS

This report represents an extensive review of the present state of scientific knowledge and technology regarding water pollution problems associated with the practice of irrigation and occurring in irrigation return flow. A large volume of literature was reviewed. Much of the information relating to return flow was found in obscure publications and reports not included in abstract journals or otherwise readily available. Most of the information contained in this literature was only indirectly related to return flow. Examples of such information include that on the persistence of pesticides in soils and their transport in water, the adverse effects of plant nutrients in water, and the disposal of sewage effluent by irrigation. There was evidence of considerable current research being conducted on pollution problems of the Colorado River Basin, in the San Joaquin Valley of California, and in the Columbia River Basin. Most of the data and conclusions are for the western United States, where most of the irrigated acreage is located and where the number and magnitude of the problems associated with irrigation return flow are concentrated. Most of the information can, however, be applied to specific situations in the more humid sections.

Irrigation return flow is water diverted for irrigation purposes that finds its way back into a supply. It includes bypass water, seepage, deep percolation and tailwater runoff. Through irrigation return flow salts are concentrated by evapotranspiration, and other substances, are conveyed from irrigated lands to the common stream or to the groundwater supply. Return flow from irrigated land may be augmented and polluted from sources not concerned with irrigation, such as rainfall, groundwater seepage, runoff from urban and industrial sites, highways, non-agricultural lands, and discharges from municipal and industrial sources.

The acreage irrigated and the water consumed are indicative of the magnitude of the return flow problem. In 1965 there were 110.8 bgd diverted to serve 42 million acres. Of this an estimated 64.7 bgd were consumed. The pollution aspect of irrigation return flow deals with the inevitable concentration of soluble salts caused by the consumption of water. The major problems associated with the quality of return flow are primarily in the arid portions of the western states where users compete for the supply. Of the irrigated acreage within the conterminous United States, about 80 percent falls within the area in which the water demands exceed or will exceed the supply by 1980. This report deals with the complicated problems related to the quality of return water and the effect on water used for irrigation and other purposes.

Many water quality changes and combinations of changes take place during irrigation. These changes are influenced by: (a) biochemical action such as fixation of nitrogen, mineralization of organic matter, reduction of nitrate and biodegradation, (b) erosion, (c) evaporation and transpiration, (d) filtration, (e) heat transfer, (f) ion exchange, (g) leaching, (h) precipitation, and (e) sorption and chelation. Not all of the effects are harmful. Although salts are being concentrated, other pollutants may be removed. Nutrients and organic wastes deposited on the land may be used by the crops, fixed by the soil, or degraded so they are not combined in the return flow. Residual salts often become a part of the return flow.

Irrigation drainage water which has moved through the soil has quality characteristics different from the surface runoff. The following changes can be expected in drainage water passing through the soil:

1. Greater concentration of dissolved solids than in the applied water.

2. Different proportion of the various ions, with a likely increase in the proportion of sodium and chloride.

3. Total salt load increased or decreased, depending on the amount of leaching.

4. Little or no colloidal or sediment material.

5. More or less nitrate content than in the applied water, depending on the original content of the water and the fertility of the soil. The most likely situation for an increase is when an abundance of fertilizer is applied to a high value crop grown on an open or sandy soil and lavishly irrigated. Seasonal variation is usual.

6. A decrease in phosphorus if the content in the applied water was high, and an increase if low.

7. A reduction in all degradable pesticides and detergents is most likely.

8. A decrease in the oxidizable organics, pathogenic organisms and coliform bacteria.

9. Chlorinated hydrocarbons do not move through the soil in appreciable concentrations and into drainage effluent. If appreciable concentrations are present in the irrigation water they will be largely removed by the soil.

10. When sewage effluent is used for irrigation it is probable that there will be a reduction in the concentration of all pollutants except the common soluble salts.

The following changes can be expected in surface runoff from irrigated land:

1. Highly variable in amount and composition for any given area.

2. Total dissolved salts only slightly greater than in the applied water. Can be less when diluted by rain or mixed with other runoff water.

3. Phosphorus and persistent pesticides are sorbed and are likely to move with soil particles and, therefore, their pollution presence in surface water is correlated with the amount of erosion.

4. Colloidal content and sediment load can be more or less than the applied water, but greater than in subsurface flow.

5. Surface water is subject to receiving pollutants directly during application from accidental discharge, from cleaning equipment, and from water to which pesticides and fertilizers are being applied.

6. Urban and rural runoff becomes commingled with irrigation return flow. These waters may carry such pollutants as plant nutrients, pesticides, and animal wastes.

7. Sporadic use of fertilizers and pesticides accounts for considerable variation in the composition of surface return flow.

Only a limited amount of data is available on the nutrient content of return flow water and on the effects of kinds of fertilizers and methods of application. The effects of slow release fertilizers on pollution reduction has not been determined. Some confusion exists as to the basis of reporting the nitrate and phosphate. In some instances, nitrate is reported as nitrogen and in others as nitrate. For phosphorus it is not always clear as to whether the data is in terms of P, PO_4, or P_2O_5. Little or no data are reported where phosphate concentrations are less than one mg/l.

Sprinkler application, pump back, reuse of tail waters, etc., results in greater application efficiency. As the efficiency is increased, an increase in the salt concentration of the return flow can be expected. An improvement in conveyance efficiency should result in less seepage loss and leaching from non-irrigated soils, with a somewhat offsetting reduction in salinity.

Salt balance evaluation of a given area or basin is of limited value. If the outflow of salt is less than the inflow, then salts are accumulating. If the outflow is greater there is still no assurance that salt is not accumulating in some of the irrigated land and being leached by seepage, etc. from non-irrigated portions of the basin. It is also possible to have salt accumulating in a portion of the soils and being leached from others with an overall balance. Applying the salt balance concept to other pollutants is meaningless because of the many interactions and reactions by the pollutants within the soils and the conveyance water.

There appears to be only a limited basis for the often quoted conclusion that salt concentrations in return flows are from five to 10 times higher than in the original water. In several controlled studies the range was 2.5 to 5. More cases would probably fall within the range of two to seven. The concentration varies greatly with time and space. Even after careful study it is difficult to predict the composition of the drainage water for a given area; e.g., the variation in estimates of the salt content of the San Luis drain and the change of concentration with time.

Data in the review indicate that salt concentration in the drainage water for a given area, when irrigated and adequately drained, decreases with time. This decrease should continue to an equilibrium. The concentration at equilibrium should be approximately equal to the mass of salt in the irrigation water, plus the mass of salt being released by contemporary weathering of the soil, divided by the quantity of drainage water. Thus, the concentration increase should be only slightly greater than the volume decrease. Deviation from such a concentration is dependent on the amount of residual salt being removed from the irrigated soils and the amount coming from the non-irrigated areas. The only fundamental management change to reduce the salt load and concentration without additional water or desalting would be to reduce the salt contribution from the non-irrigated areas and/or eliminate the irrigated acreage having a high residual salt content.

Changes in use patterns such as the current decrease in the use of chlorinated hydrocarbon pesticides and a tendency to more carefully follow application instructions alter the pesticide pollution problems, new materials and methods of pest control will require continuing research to regulate the impact on the quality of return flow.

There is little information on which to base conclusions as to the effect of irrigation on the temperature of return flow water, except that there seems to be a moderating effect. Through water storage there is an opportunity to regulate temperature of release water by drawing water from different levels of the impoundment.

Impoundment of water in multipurpose reservoirs has numerous effects on the quality of water, both beneficial and detrimental. Among the beneficial effects are decreases in coliform bacteria, color, turbidity, suspended matter, BOD, and a leveling effect on temperature and chemical quality. The adverse effects usually include a decrease in oxygen and increases in alkalinity, iron, manganese, algae, and total salinity. Often there is precipitation of calcium carbonate, resulting in an increase in the proportion of sodium ions in solution.

Studies have been made on the feasibility of treating and disposing of return flow water having salt concentrations too great for further use. Desalting for irrigation does not appear to be an economical solution except under unusual circumstances and then only where dual purpose plants are used. Bypass drains are used in the San Joaquin Valley of California, where the nitrate is removed before discharge, and for the Wellton-Mohawk project in Arizona.

Pollutants in return flow water can have adverse effects on other water uses and on re-use for irrigation. Likewise, pollutants from other sources may have adverse effects on irrigation agriculture. This is particularly true of the boron discharged by municipalities and industry. In general, the more numerous the pollutants and the greater the concentration, the less the value of an increment of water for irrigation or for any other use.

The unique and extremely difficult economic problems related to irrigation return flows involve external economies and diseconomies. The market and price system does not function well in resolving these problems. Apparently special institutional and organizational arrangements must be devised. Basic to these programs are appraisals of economic impacts of various alternatives. These appraisals involve complex conceptual considerations and difficult empirical relations. Critical methodology and data needs are apparent.

A substantial conceptual economic framework related to this problem has been developed. Some experimental work on basic physical relationships is available and in process. However, practically no empirical study has been made of the economics of irrigation return flows. Increased attention is being given to research projects of a related nature. A need exists for economic research explicitly concerned with the subject.

From the legal standpoint, irrigation return flows have been regarded as part of the water resource and laws have been on the statute books for over half a century outlining how rights to these waters can be obtained. Statutes and court decisions have been concerned with the quantity of return flow and the laws have been virtually silent on the quality aspects of the return flow problem. National concern over water pollution has led to state and national legislation concerning quality standards which are becoming the concern of all irrigation projects.

INTRODUCTION

The nation's growing determination to control or abate pollution, culminating in the Water Pollution Control Act of 1965 which provided for state water quality standards, has raised many questions about the nature and extent of water quality changes resulting from irrigation. This is a complex subject. It has economic, political, legal, and philosophical implications, as well as physical and technological ones. For more than a century irrigation has been utilized in developing the land and water resources of the West. Recently irrigation to supplement rain and alleviate drought has been initiated throughout the usually humid East.

In irrigation, pure water is extracted by the plants from the water supply, resulting in an inevitable concentration of those dissolved solids which are characteristic of all natural water supplies. Other uses add something to the water, but irrigation basically takes some of the water away, concentrating the residual salts. Irrigation may also add substances by leaching natural salts or other materials from the soil or washing them from the surface.

Irrigation return flow is a process by which the concentrated salts and other substances are conveyed from agricultural lands to the common stream or the underground water supply. This study is concerned primarily with the physical and chemical processes as they are now understood, with possible ways to alleviate detrimental effects, and with economic and legal aspects of the problem.

Development of Irrigation in the United States

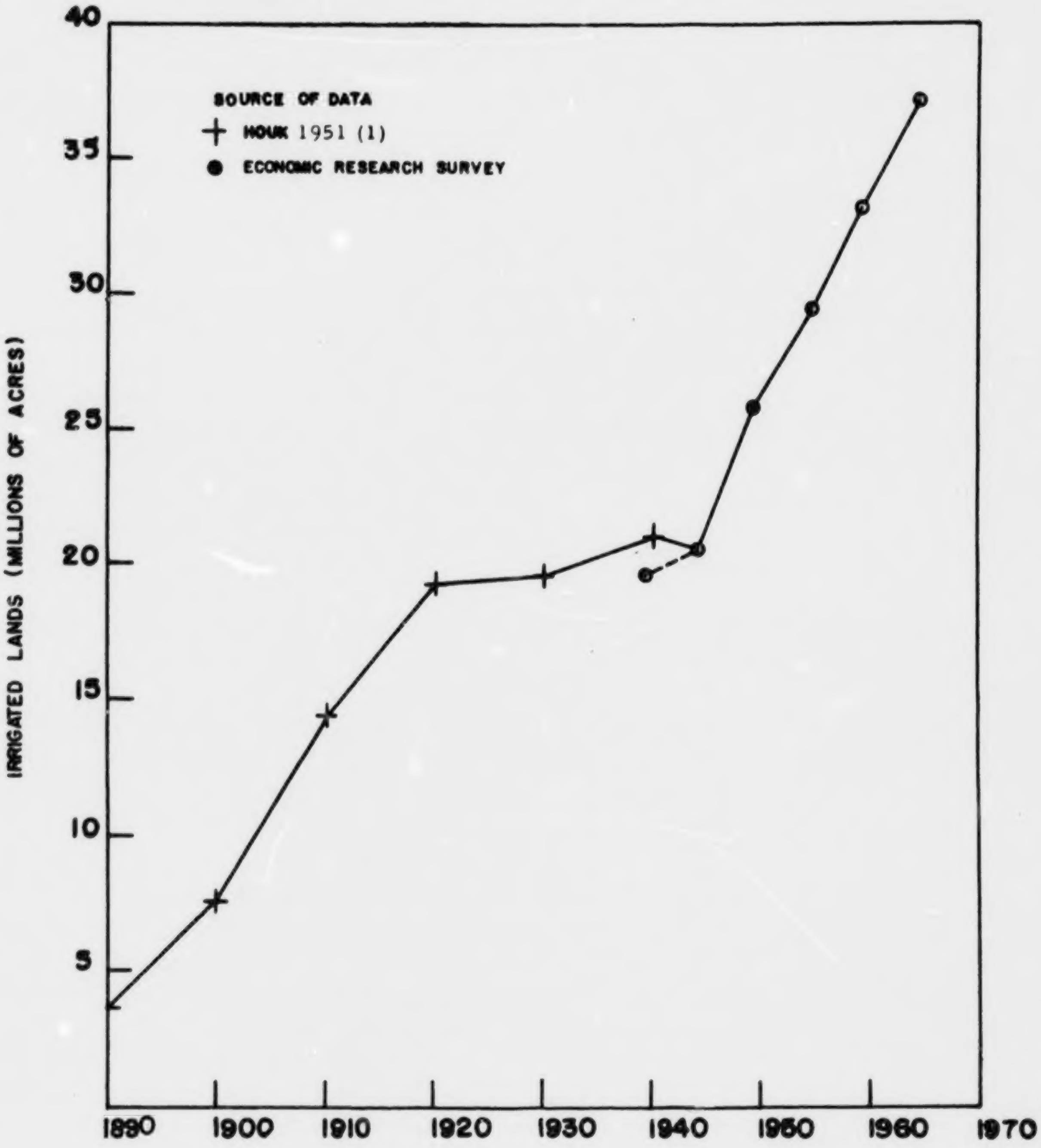
Irrigation is perhaps one of the most important practices developed by man. It is an ancient art. Early civilizations in Egypt, Mesopotamia, China, and America were founded on irrigation. Reference to its use is found in the Bible. Many ancient irrigation projects fell into disuse for reasons not now clear. Drainage and salt problems were major factors. Greater production control can be achieved under irrigation than with any other system of farming. The importance of irrigation in maximizing agricultural production can hardly be over-emphasized. Irrigation was being practiced by the Indians of both North and South America when Columbus made his historic voyage, and remnants of these old systems can still be seen, some still being used, others barely discernable (1). Modern irrigation in the United States is generally recognized to have had its beginning during the middle of the nineteenth century with the settlement of Utah by the Mormons and the "gold rush" to California. The expansion of irrigation in the United States is shown in Figure 1.

In the past 75 years the total irrigated land in the United States has increased from under four million acres to over 37 million acres, or an increase of nearly 1,000 percent. Water diverted for irrigation in 1965 amounted to 110.8 bgd with consumption estimated at 64.7 bgd serving an area of 42 million acres (2). During the last two decades, the value of supplemental irrigation has been recognized in the humid eastern United States. This now totals nearly four million acres. There is every reason to believe that the acreage of irrigated lands will continue to increase as demands for food production increase.

Economic Importance of Irrigation

A detailed report of the economic importance of irrigation is not appropriate in this report. However, some indication of the role of irrigation in the agricultural and national economy seems in order. The following statement from the Economic Research Service (3) points this out:

> First, yields per irrigated acre are often several times those obtained for the same crop grown without irrigation. For example, in 1954 yields of irrigated cotton in the West were about two and a half times as much per acre as non-irrigated cotton throughout the United States. The U. S. Department of Agriculture estimated for 1954 that irrigated pasture in the West yielded about ten times as many pounds of forage per acre as non-irrigated pasture throughout the United States.
>
> High-valued crops, combined with higher yields per acre, are concentrated on irrigated land. Irrigated cropland harvested made up less than ten percent of the total cropland harvested in the United States in 1959. Yet, well over a third of the total U. S. acreage in orchards and vineyards and over 30 percent of the acreage of vegetables harvested for sale were found on irrigated land in the seventeen western states.
>
> Finally, irrigated feed crops and pasture play a significant part in stabilizing the western livestock industry by providing a dependable feed base that permits more effective use of the extensive pasture areas,



IRRIGATED LAND IN FARMS IN THE UNITED STATES

Figure 1.

> as well as the growth of large-scale livestock finishing operations near western population centers.

It is reported (4) that 25 percent of the total value of all crop production was derived from the irrigated cropland, representing ten percent of the total crop acreage.

Importance and Mechanics of Return Flow

The importance of irrigation return flow as a source of supply for downstream users was recognized early. Newell (5) states:

> This effect of irrigation in increasing natural seepage is now well recognized, and it is often esteemed as benefit to lower portions of a valley to have water applied to lands higher up, since, by so doing, the amount available in the latter part of the crop season for the lower land is increased.

Others, including Mead (6) and Wilson (7) have made similar observations.

Much of the water diverted for irrigation purposes is consumed by the crop, but some of it finds its way back into a stream or the underground source of supply and may be reused. Only that water which is actually consumed is not subject to return flow.

Water consumed is considered to be that water which is changed from the liquid to the vapor state by evaporation or transpiration. Irrigation return flow may come from the following sources: seepage -- water seeping from canals, ditches, and other structures comprising the conveyance and distribution system; bypass water -- water which is returned directly to the river or source of supply without being applied to the irrigated land; deep percolation -- applied irrigation water which finds its way to the drainage system or contributes to the groundwater recharge; tail water runoff (waste water) -- that portion of the applied water that runs off the land surface. Thus, irrigation return flow is defined as "any water diverted for irrigation purposes that finds its way back into a source of supply -- stream or groundwater basin" (see Figure 2).

Return flow from all of the above sources may be subject to augmentation and pollution from sources not connected with irrigation; i.e., precipitation, groundwater seepage, surface runoff from urban areas, highways, and non-agricultural lands, and discharges from industrial sources may commingle with irrigation return flow. Quantity, quality, nature, and extent of pollution from commingled waters

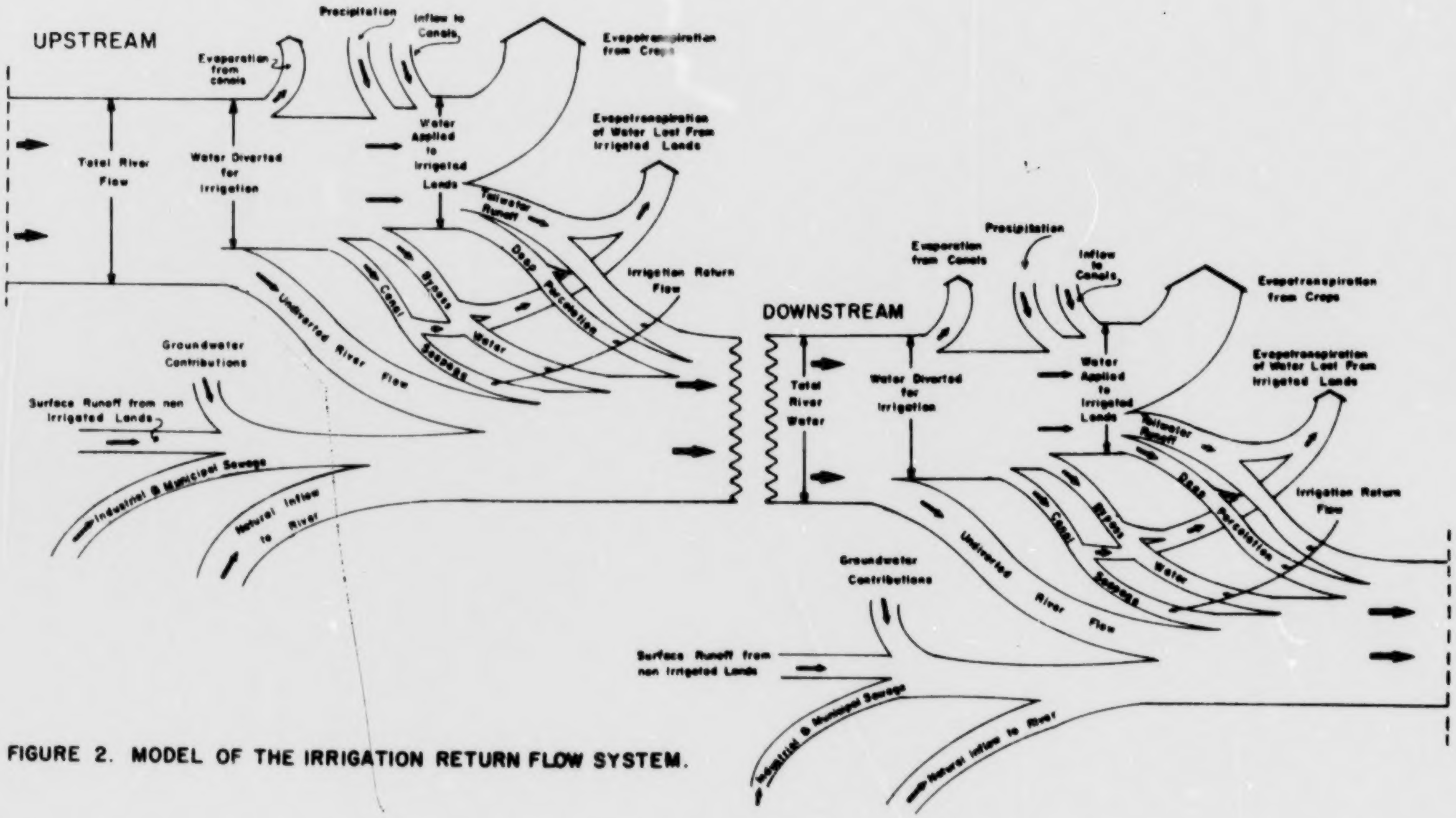

UPSTREAM
Total River Flow
Water Diverted for Irrigation
Evaporation from canals
Precipitation
Inflow to Canals
Water Applied to Irrigated Lands
Evapotranspiration from Crops
Evapotranspiration of Water Lost From Irrigated Lands
Tailwater Runoff
Deep Percolation
Bypass
Canal
Seepage
Water
Irrigation Return Flow
Undiverted River Flow
Groundwater Contributions
Surface Runoff from non Irrigated Lands
Industrial & Municipal Sewage
Natural Inflow to River
DOWNSTREAM
Total River Water
Water Diverted for Irrigation
Evaporation from Canals
Precipitation
Inflow to Canals
Water Applied to Irrigated Lands
Evapotranspiration from Crops
Evapotranspiration of Water Lost From Irrigated Lands
Tailwater Runoff
Deep Percolation
Bypass
Canal
Seepage
Water
Irrigation Return Flow
Undiverted River Flow
Groundwater Contributions
Surface Runoff from non Irrigated Lands
Industrial & Municipal Sewage
Natural Inflow to River

FIGURE 2. MODEL OF THE IRRIGATION RETURN FLOW SYSTEM.

have not been isolated or evaluated. This is difficult, but it is necessary to properly assess the quality and pollution role of each water use affecting the water supply.

As indicated by the definition, and as shown in Figure 2, the mechanics of irrigation return flow are not simple. The operation of the canal system itself may modify the water supply at the field, both in amount and quality. A portion of the water diverted will be lost as seepage through the canal bed and banks. Part of this "seepage water" will be transpired immediately by vegetation growing along the canal right of way; the balance will find its way into some groundwater system and may ultimately appear as irrigation return flow. In open conveyance systems, a portion of the water diverted will be evaporated from the free water surface. In all irrigation systems both seepage and evaporation losses usually occur. Partially offsetting these losses, the canal may receive water directly from precipitation, through influent seepage, from cross-drainage inflows or drainage from lands and other sources along the canal. Some of the water diverted to an irrigation canal is used only to maintain head in the system for one purpose or another (i. e., flow regulation, measurement, screening, etc.) resulting in operational losses which are returned directly to the river.

Of the water applied to the land for irrigation, a portion is stored within the root zone and consumptively used by the crop. Water not so stored may percolate below the root zone (deep percolation losses) or a part of it may run off the field at the end of the irrigation run (tail water runoff) to be pumped back and reused. Tail water runoff not reused will find its way into surface or underground drainage systems, ultimately to appear as irrigation return flow, but the quantity and quality will very likely be changed en route. The water percolating below the root zone may move laterally to seepage areas or deeply into the groundwater basin to join other water and become a part of the hydrologic system.

The model of the irrigation return flow system proposed in Figure 2 indicates that the water diverted for irrigation at any point along a stream may be comprised of both virgin flow of the stream and return flow. The proportion of applied water appearing in return flow may vary from zero to nearly one-hundred percent. For example, on the lower Sevier River in Utah, practically all of the water diverted at certain seasons of the year is return flow. It is mostly from irrigation, but it also comes from such other sources as municipal and industrial waste water. The cycle of diversions and return flow illustrated in Figure 2 is repeated many times on the Sevier River, for there are numerous diversions, seven of which take the entire flow at the point of diversion (8).

The diversion-return-flow cycle shown in Figure 2 is typical of many western rivers. The water in the river at any point is composed of natural inflow, irrigation return flow, and return flow of other used water, the proportions depending upon the number of diversions, the extent and diversity of use, the position on the stream, and the natural inflow or "make" of the stream.

Nature and Extent of the Pollution Problem of Irrigation Return Flows

Although there are many aspects of irrigation return flow, the principal two are the quantity of water and the salt content. Salt is a natural product of geologic weathering. Pillsbury (9) developed a relationship between water production and salt production on several western watersheds. Figure 3 indicates that salt production in the streams studied varied from 0.1 tons/a.f. on streams producing 1000 a.f./sq.mi. to over 5 tons/a.f. on streams producing only 1.0 a.f./sq. mi.

Over the ages the rivers have carried this salt load to the oceans. This important role of precipitation and drainage into streams and rivers, although coming about naturally, maintains the quantity of dissolved minerals in the soil at levels which permit plant growth. In changing from natural vegetation to agricultural crops and imposing irrigation, man has diverted the salt with the irrigation water and applied it to agricultural land. The diverted salt must be removed from the agricultural land; otherwise, the lands become too saline for continued agriculture. The major problem is in transporting this total salt in the reduced streamflow and dealing with the increased concentration of the salts downstream. Many agriculturalists question whether this concentration effect really should be called pollution. Pollution or not, the salts must be dealt with, they must be removed from the agricultural land and disposed of in acceptable ways. In commenting on this problem, Quigley (8), formerly Commissioner of FWPCA, had the following to say:

> Salt-laden return flows from irrigation systems admittedly constitute a difficult technical and engineering problem, but here too there is room for improvement in the overall management of many of our irrigation systems. Once it has been accepted that the problem must be dealt with, both the economics and the technology will be worked out, just as the economics and the technology of dealing with many industrial wastes will be worked out.

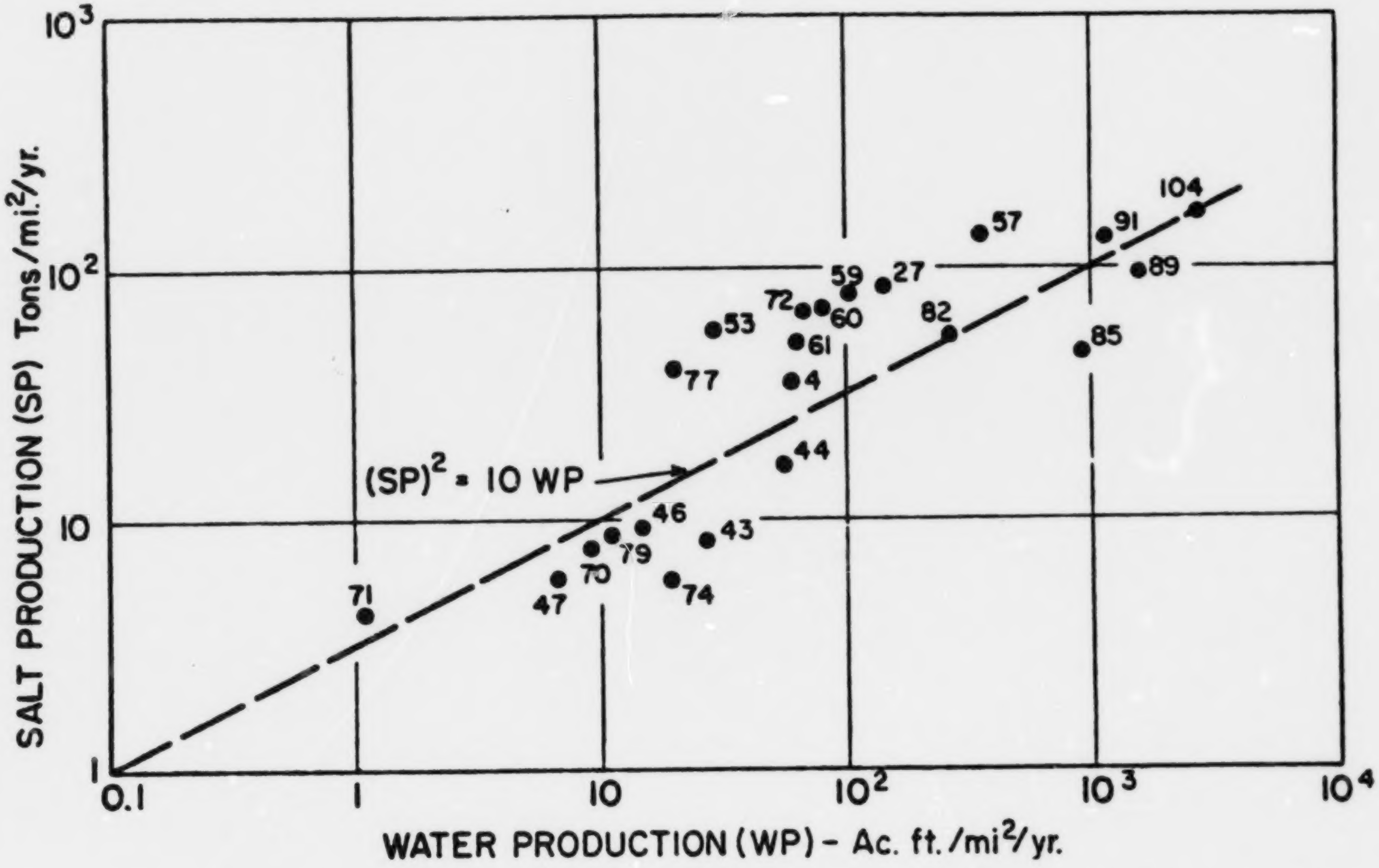


Figure 3. Approximate relationship of salt production to water production for several rivers in the Western United States (9).

Normally, salt diverted in the practice of irrigated agriculture is returned to the river with a portion of the water diverted. Thus, the salts are linked back to the water course in which they would have been transported naturally, but by a smaller quantity of water. This increases the concentration which often is objectionable to certain downstream users. Each successive diversion and irrigation cycle on a stream further increases the salt concentration. Under ideal salt balance conditions (no buildup of salt in the lands), the residual flow entering the oceans would contain all of the salts that would have been transported by the pristine river if none of the water had been diverted and consumptively used to produce crops. "Return flow is the mechanism by which all the salt imported to the project through the diversion can be returned to the river" (9).

Superimposed upon the interruption in the natural flow of salts to the sea by the irrigation diversion is the imposition of fertilizers and pesticides into the cycle. The extent to which these are dissolved or suspended and transported by irrigation water to appear in irrigation return flow has only been partially investigated. The implications have not yet been well defined. Nevertheless, to the degree these are a source of added pollution, they must be dealt with in the interest of society.

Relation of Irrigation Return Flow Problems to Present Legislative Water Quality Standards and General Pollution Control Problems

Irrigation return flow has long been considered to be beneficial because it was a recognized source of supply for the irrigated areas further downstream. This was observed by Newell (5), Mead (6), Wilson (7), and was further emphasized by Hutchins (10) in the following quote:

> Return flow is a common phenomenon in western irrigated regions and many water rights are predicated wholly or partly upon it. For example, on streams such as the Provo River in Utah, downstream development occurred first, and return flow from junior upstream diversions not only satisfied the requirements of earlier downstream appropriation, but actually benefited them by prolonging the seasonal supply. On the other hand, on the South Platte in Colorado, upstream development occurred first and the increasing return flow made progressive downstream development possible and eventually added materially to the value of the junior downstream rights.

Most of the western states have legislation dealing with the procedures for acquiring rights to return flow. In addition, numerous court decisions have been rendered regarding the ownership of return flow water. In most all cases, the return flow was considered to be a beneficial resource and its ownership was highly valued. The major concern of water rights legislation and administration has been with ownership and total water supply. At this level, little thought or attention has been given to water quality and pollution, although quality has been considered in irrigation projects planning for a number of years, and state health authorities have been concerned about pollution of water for domestic supplies. Interstate compacts, treaties, and irrigation water rights have generally been silent on the matter of quality and especially so as it concerns dissolved salts. However, the mounting public concern over water pollution and resulting legislation in recent years requires a consideration of all possible vectors in the pollution spectrum. Thus irrigation return flow, because of its generally high salt content and the possibility of transmitting other agricultural pollutants into public water supplies, has come under increasing scrutiny.

The Federal Water Pollution Control Act (1948) with amendments marked a major entry of the federal government into active participation in water quality control. However, the issue of dissolved solids in irrigation return flow as a pollutant was hardly raised. The Water Quality Act of 1965 authorized the states to establish water quality standards on all interstate streams and coastal waters, thus including irrigation return flow. Irrigated agriculture must, therefore, become concerned with water quality standards and with general pollution control legislation. National policy, philosophy, and legislation concerned with the pollution aspects of irrigation return flow must be developed carefully in order not to jeopardize the vast economy that is based on irrigated agriculture. It must permit the wise and prudent use of water and still maintain or substitute for the natural processes in the undepleted rivers in keeping the salt balance of the river drainage basins.

Special Problems Due to Consumptive Use

The quality problem raised by irrigation return flow is of special concern because irrigated agriculture is the largest consumer of public water supplies. Most municipal, industrial, and recreational uses of water do not consume much of the water; that is, they do not change it from the liquid to the vapor phase, but only use the water for the purpose intended, adding various pollutants in the process, but returning most of the used water. Irrigated agriculture, on the other hand, diverts large quantities of water, consumes from one-third to one-half or more of the total water diverted, and returns the balance to the streams and underground supply as irrigation return flow, presumably transporting all of the dissolved solids diverted back into the stream. Water consumption by agricultural crops may range from 5,000 to 10,000 gallons per acre per day, whereas the actual consumption by man to satisfy his normal body functions is less than one gallon per person per day.

While increasing salt concentration, the agricultural process may, on the other hand, remove other pollutants. For example, nutrients and other organic wastes deposited on agricultural land with irrigation water may be used by the crop, fixed by the soil, or degraded so that they are not contained in the irrigation return flow.

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IRRIGATION PRACTICE

Mechanics of Irrigation Practice

Irrigation practice involves the control of water on the land in order to manage the soil moisture environment to maximize agricultural production. This control extends from the diversion at the river or other source of supply to the drainage of water from the soil profile. Irrigation practice, therefore, includes diversion, conveyance, measurement, application, cultivation, pump back or reuse, runoff, and drainage. The complexity of the irrigation process and the age-old custom it represents has led many to refer to irrigation as an "art" rather than a science. True, many of the principles of good irrigation practice have been handed down from generation to generation, and only in recent years have the various sciences been applied to the practice of irrigation. Today's irrigation engineer, designing and operating irrigation projects, should have knowledge or professional support in the following technical areas: hydrology, fluid mechanics, water requirements of crops, methods of water delivery, methods of water application, water rights, soils, plants, fertilizers, pesticides, soil physics, infiltration, movement of water in soils, drainage, cultivation requirements, and a general knowledge of agricultural production under irrigation.

Most important from the standpoint of irrigation return flow are the problems of water application methods, soil moisture storage, evapotranspiration, salt balance concepts, nutrients, pesticides, drainage, and their interrelationships which alter the quality of the irrigation return flow.

Application methods

In the process of irrigating crops, water is applied to the soil by one of several methods, including surface irrigation (furrows, basins, borders, etc.), sprinkler irrigation and subsurface application.

The effect of the method of application on quality and quantity of irrigation return flows has not been given detailed study. However, it stands to reason that surface methods of application will be most important in relation to tail water runoff and may, therefore, have a more prominent role in transporting pollutants originating or available

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above or at the soil surface. Modern methods of irrigation and emphasis on irrigation efficiency have greatly reduced the proportion of surface runoff. In many systems, such as furrow irrigation, farmers have collected the surface runoff and employed "pump back" systems to salvage water formerly lost. In other systems the plans of the irrigation layout have been made to prevent or recapture the runoff. This is only natural since surface runoff is the one loss the irrigator can observe, while seepage and deep percolation are not so obvious.

Sprinkler irrigation and subirrigation methods will affect the quality of waters infiltrating in and percolating through the soil, for surface runoff should not be a factor with these methods. Sprinkler irrigation may also be a factor in washing pesticide residues from plant leaves or in washing certain pollutants from the air.

Soil moisture storage

Irrigation is the practice of supplementing natural precipitation by applying water to the soil. Water is stored within the root zone and later used by agricultural crops. During the irrigation process, the soil is seldom completely saturated, although during and immediately following irrigation considerable gravitational or free water may be found in the pore space of the soil. Depending upon internal drainage conditions and the use of water by crops, the gravitational water moves below the plant root zone and the remaining water surrounding the soil particles is held by capillary forces under tension. This capillary moisture moves only slowly if at all through the soil and is said to be stored in the soil. This moisture is available for use by agricultural crops which must exert tension forces to extract it from the soil. As water is taken up by the plant roots or evaporated, the tension on the remaining water gradually increases until the plants can no longer extract sufficient amounts to meet their daily requirements. Wilting takes place and unless additional water is provided, the plants die. To characterize these various soil moisture levels, irrigation scientists have defined the following terms: saturation -- water within the soil profile completely filling all of the pore space, a condition generally considered to exist below the water table; water table -- the level at which the soil water is maintained at atmospheric pressure, the boundary line between saturated and unsaturated soil; field moisture capacity -- usually considered to be the amount of water (percentage) that a well-drained agricultural soil will hold within the root zone against gravitational forces, and also considered to be a moisture tension in the soil of 0.1 to 0.2 atmospheres; wilting point -- the moisture retained by the soil after permanent wilting of plants, and this varies with different plants (approximately 15 atmospheres); available moisture -- the water stored in the plant root zone under tension forces between 0.1 and 15 atmospheres. Considered to be the capillary water existing between field capacity and the wilting point; readily available moisture -- that portion of the stored water that can be used by crops without developing high tension forces; and stored water -- water stored within the plant root zone to be used by agricultural crops.

Evapotranspiration

In irrigated agriculture "evapotranspiration" refers to the evaporation or transpiration of water in the crop-producing area. It is dependent upon many factors, primarily the energy from incoming solar radiation, but available soil moisture, temperature, crop variety, stage of crop growth, length of growing season, wind, relative humidity, and other factors are involved. Evapotranspiration results in consumptive use of water averaging as much as 0.25 inches (6,700 gallons per acre) per day during the peak growing season. Daily maximums of as much as 1.0 inch per day (27,000 gallons per acre per day) have been reported. The consumptive use of water by crops (evapotranspiration) varies from 15 to 20 inches for a crop of grain to more than 60 inches for citrus and alfalfa which grow all year.

The most important factor in the relationship of evapotranspiration and irrigation return flow is that the water consumed is relatively pure water, the dissolved solids being left in the soil as precipitates or dissolved in the water not consumed. Thus, the process has the effect of concentrating the total salt load in the fraction of the water returned to the stream as return flow.

Salt Balance Concept

The general salt balance concept introduced by Schofield (11) relates the amount of soluble salt brought into a given area by irrigation water to the amount discharged by the drainage water. Unless the same quantity is removed that is added an accumulation of salt occurs and the land cannot be kept permanently in crops. This concept can be applied to a given piece of land or to an entire watershed. For the common salts in river water, the concept is expressed by an equation:

$$Q_iC + S_w + \text{others} - (Q_dC + S_{ppt} + S_c) = 0$$

where

Q_i = quantity of irrigation water

Q_d = quantity of drainage water

C = concentration of salt

S_w = salt from weathering

S_{ppt} = salt precipitated

S_c = salt in the crops

This concept is intended as a useful tool in the control of salinity on the land and for water management. Wilcox and Resch (12) pioneered a salt balance and leaching requirement study on the Rio Grande Project and concluded that salt balance is a reliable and useful indicator of year-to-year trends in salinity conditions. When applied to a large area it can be misleading because inadequate leaching and salt accumulation can occur in one portion of the region while leaching of previously accumulated salt can occur from another portion, with a resulting apparently favorable overall balance.

Concentration of salts

A concentration of soluble salts is an unavoidable result of consumptive use of water by irrigated crops. As water is evaporated or transpired by the crop, salts in the irrigation water applied to the land are necessarily concentrated. The major portion of the mass of salts in the applied irrigation water remains soluble in the soil solution. Some of the less soluble salts, such as calcium carbonate, may precipitate in the soil. To maintain a favorable salt balance, and a permanent agriculture, a more saline water must leave the land area as "return flow" either by percolating below the root zone into the ground water or through a natural or artificial drainage system.

Leaching

To prevent an accumulation of soluble salts in the soil and thus maintain a favorable salt balance in the root zone, the land should receive water in excess of that required by the crop so that the excess can pass through the soil profile and leach out the soluble salts. The amount of water required for leaching, known as the leaching requirement, is determined by the concentration of salt in the irrigation water and the concentration in the soil solution that can be tolerated by the crop. As defined by the U. S. Salinity Laboratory (13), the leaching ratio (LR) is the proportion of the irrigation water that must pass from the soil as drainage water in order to maintain a favorable salt balance in the soil. This can be expressed as:

$$LR = D_d/D_i = C_i/C_d$$

where

LR = leaching ratio

D_d = depth of drainage water removed

D_i = depth of irrigation water applied

C_i = concentration of salts in the irrigation water

C_d = concentration of the drainage water

The ratio may also be expressed in terms of electrical conductivities EC_i/EC_d. In this equation, only the water and salt added as irrigation water and the salt removed by the drainage water are considered. Where other salts are involved or the rainfall is appreciable, adjustments, such as shown by Reeve and Fireman (14) or by Bouwer (15), can be made. Where the quality of the return flow water for reuse is of concern, the amount of leaching water may need to be increased in order to provide dilution of the salts. In practice, maintaining the salt balance has been given priority, and the resulting quality of drainage water has seldom been considered. The leaching requirement is specific for any specified conditions of crop tolerance, concentration of irrigation water and quality of the return flow. The usual range is 10 to 30 percent. The amount of leaching water provided under usual irrigation practices (irrigation efficiency 50 to 70 percent) is 30 to 50 percent.

Ion exchange

Normal soils contain appreciable quantities of calcium, magnesium, potassium, and hydrogen in ionic form held to the soil particles in an exchangeable form. As irrigation water is evaporated and transpired, the concentration of salts in the soil solution increases. These salts are in ionic form and some of the cations in solution replace some of the cations held by the soil. The equilibrium level of sodium on the soil depends on the proportion of sodium in the soil solution. A high proportion induces a replacement of calcium and magnesium on the soil particles by sodium. Both soils and plants are adversely affected by high levels of exchangeable sodium. The U. S. Salinity Laboratory (13) developed the exchangeable sodium adsorption ratio (SAR) for irrigation waters:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{++} + \mathrm{Mg}^{++}}{2}}}$$

the Na^{+}, Ca^{++} and Mg^{++} are expressed as milliequivalents per liter. As an index of the danger of adverse sodium effects, for sensitive fruit crops, the tolerance limit for SAR may be as low as 4. For more tolerant general field crops, the limit is likely to be within the range of 8 to 16. This, however, varies with such soil factors as texture and the kind of clay minerals present.

Chemical fixation and precipitation

In addition to concentrating salts and altering the proportion of calcium and sodium by ionic exchange, there are several other possible changes in the composition of irrigation water as it passes on to the return flow. One of these changes is the precipitation of calcium carbonate. In the presence of bicarbonate ions in the water, calcium is precipitated as the relatively insoluble carbonate and the sodium salt remains in solution. This results in an increase of the proportion of sodium in the soil solution in a higher SAR value, and an increased sodium hazard.

Phosphates in water at relatively high concentrations may be reduced by precipitation as slightly soluble calcium phosphates and iron and aluminum phosphates, or be "fixed" by lime in the soils. Whether drainage water contains more or less phosphate than the irrigation water depends on such factors as the amount in the irrigation water when applied and the nature of the soil being irrigated.

A number of other soluble constituents in the irrigation water, such as the heavy metals, are likely to occur in less concentration in the return flow than in the applied water when there are appreciable amounts in the irrigation water. Sources of heavy metals in the irrigation water are pesticides, impurities in fertilizers, particularly phosphates, wastes from gasoline combustion and coal combustion, metal smelting, etc., and washed from the air by rain and snow. In the process of irrigation the metals are largely removed by the soil as precipitates, as chelation in living organisms, or by the organic matter in the soil. Heavy metals held by the soil are difficult to remove and tend to stay in the soil as pollutants rather than move out with the drainage water.

Nutrients

The plant nutrients nitrogen and phosphorus stimulate aquatic plant growth in water of storage and conveyance systems. Nitrate-nitrogen is highly soluble and moves with water. The salt balance concept is difficult to apply to nitrate because of the many sources as well as possible losses. The nature of the complexity is indicated in a nitrate balance equation:

$$(Q_iC_n + NO_{3_{om}} + NO_{3_{rf}} + NO_{3_f}) - (NO_{3_c} + NO_{3_f}) = Q_dC_n$$

where

Q_i = quantity of irrigation water

C_n = nitrate concentration

$NO_{3_{om}}$ = nitrate from organic matter

$NO_{3_{rf}}$ = nitrate from rain and fixation

NO_{3_f} = nitrate from fertilizers

NO_{3_c} = nitrate removed by crops

NO_{3_r} = nitrate removed by reduction

Q_d = quantity of drainage water

It is evident that irrigation may add to or remove nitrate from water being used for irrigation so the nitrate concentration of the return flow may be either greater or less than in irrigation water. An important aspect in nitrate pollution abatement is the identification and control of the major sources.

As previously indicated, phosphate does not behave as a soluble salt, such a sodium chloride, which is relatively easy to leach from the soil and into the return flow. Evaluations are further complicated by the fact that phosphorus can exist in water in at least five norms: soluble orthophosphates, soluble organics, insoluble organics, adsorbed on suspended materials, and as a component of suspended minerals and organic matter.

The salt balance concept is likewise difficult to apply because of the many sources of phosphate to the soil and the numerous reactions influencing its concentration in the soil solution. This is illustrated by the following terms which are dynamic and difficult to evaluate:

$$(Q_iC_{pi} + P_f + P_o + P_p + P_s) - (Q_dC_{pd} + P_{pa} + P_c + P_e) = ?$$

where

Q_i = quantity of irrigation water

C_{pi} = phosphate concentration in Q

P_f = phosphate from fertilizer

P_o = phosphate from organic matter

P_p = phosphate from pesticides

P_s = phosphate from soil minerals

Q_d = quantity of drainage water

C_{pd} = phosphate concentration of drainage water

P_{pa} = phosphate precipitated and absorbed

P_c = phosphate removed by crop

P_e = phosphate removed by erosion

It is evident that there are many possible sources of phosphorus in water pollution as well as several likely ways to remove soluble phosphorus from soil and water.

Pesticides

Numerous compounds are used to control weeds, insects, etc. Some are decomposed or degraded biochemically and photochemically. Others are relatively unaltered and are adsorbed by the soil and move only with the soil. Few, if any, move through the soil in proportion to the amount of leaching. Because these processes are insufficiently understood, it is impossible to apply the salt balance concept to most of the pesticides.

Consequences to Irrigation Return Flow

The intricate nature of the water-soil-quality complex makes the prediction of the return flow variables extremely uncertain. Irrigation return flow is a dependent function which may be expressed by the following relationship:

$$IRF = f(Q_i, C_s, B, T_a, M_a, S_m, S_c, ET, D_p, C, F_p)$$

where

IP = irrigation return flow (quantity)

Q_i = quantity of irrigation water diverted

C_s = canal seepage

B = bypass water

T_a = time of application

M_a = method and rate of application

S_m = soil moisture

S_c = soil characteristics; i.e., depth, permeability, structure, texture, stratification, etc.

ET = evapotranspiration

D_p = deep percolation

C = type of crop

F_p = farm practices

Likewise, the quality of irrigation return flow is a dependent function, being controlled by the quantity of irrigation return flow as expressed above with additional quality inputs. The following relationship shows its complexity:

$$IRF_q = f(Q_{iq}, C_{sq}, B_q, T_a, M_a, S_{mq}, S_{cc}, ET, D_{pq}, C_q, F_{pq}, F_a, P_a, C_f, O_i)$$

where

IRF_q = irrigation return flow quality

Q_{iq} = quality and quantity aspects of applied irrigation water

C_{sq} = canal seepage quality change

B_q = bypass water quality

T_a = time of application

M_a = method and rate of application

S_{mq} = soil moisture quality

S_{cc} = additional soil characteristics such as cation exchange capacity, basic soil compounds, bacteriological activity, chelation, fixation, oxidation, and other factors which may alter the soil-chemistry-bacteria-water system

ET = evapotranspiration

D_{pq} = quality of water percolation below the root zone

C_q = crop influence on quality

F_{pq} = farm practice effect on quality

F_a = fertilizer application

P_a = pesticide application

C_f = climatological factors; i.e., temperature, precipitation, wind, sunshine, etc.

O_i = other influences; i.e., elements carried from the air to the farmland by precipitation, industrial pollution of soils or water, municipal inputs from runoff or sewage, etc.

Both the quantity and quality of irrigation return flow are dependent variables, with the soil and soil moisture playing important roles as shown in the above functional relationships. The soil is a dynamic chemical mass capable of exerting a major change in the quality of any water passing through it. The soil moisture regime is also undergoing constant change, with the net result being a highly variable output so far as quality and quantity of irrigation return flow are concerned.

Soil moisture regime

The soil root zone is often referred to as the storage reservoir for moisture used by the plants. Maximum storage in this reservoir is considered to be field capacity, with the minimum being the wilting point, although soils may be dried below the wilting percentage by evaporation. In the management of irrigated soils, water is usually added to the soil by precipitation or by any of several irrigation methods before the plants have depleted the moisture to the level of wilting. Sufficient moisture is usually added to bring the root zone soil to "field capacity." At this point the soil water within the root zone contains a given quantity of dissolved solids, nutrients, and other constituents, depending upon the interaction expressed in the above function for IRF_q. Irrigations in excess of the amount needed to bring the moisture level to field capacity will cause deep percolation below the root zone, with quality constituents representing the particular condition for that particular time.

If only enough water is added in a given irrigation to bring the soil to field capacity there may be little or no movement of water below the root zone. The salts and other impurities applied with the water remain in the soil, to be concentrated in the constantly decreasing amount of soil water or precipitated in the soil. Some of the cations may become associated with the soil particles in the base exchange reaction. Continued irrigations of this type coupled with the constant removal of relatively pure water by plants in the evapotranspiration process induces a salt buildup in the soil, increasing the concentration of the soil water and ultimately presenting the possibility of inhibiting plant growth. Irrigation experts have been primarily concerned with achieving the type of irrigation outlined above to eliminate deep percolation losses and only refill the root zone to field capacity at a given irrigation. It is now recognized that some water must move through the soil profile, otherwise a salt balance in the soil profile cannot be maintained.

It can be seen from the above that the time, amount, and frequency of irrigation which result in movement of water below the root zone will greatly influence the concentrations in the water moving below the root zone. Thus, the quality of the drainage water leaving the area and the resultant quality of the irrigation return flow will be affected.

Drainage water

In irrigated areas, drainage water may come from either surface sources or water which has moved through the soil profile. In either case the water may undergo substantial but different quality changes due to the unique exposure condition.

Drainage water from surface sources. This source of irrigation return flow consists mainly of surface runoff from irrigated land. Because of its limited contact and exposure at the soil surface, one might expect the water to contain the following:

(a) Dissolved solids concentration only slightly greater than in the applied irrigation water.

(b) Variable and fluctuating amounts of pesticides that have been applied.

(c) Variable amounts of fertilizers.

(d) Organic and foreign matter from households, barnyards, adjacent lands, etc.

(e) Variable amounts of sediment, colloidal and adsorbed material.

(f) Debris, crop residue and other substances floated from the soil surface.

Drainage water which has moved through the soil profile. Because of its more intimate contact with the soil and being subject to the dynamic soil moisture regime outlined above, this source of irrigation return flow water might have greatly different quality characteristics from the waters originating mainly from surface runoff. In the case of water passing through the soil profile, one might expect:

(a) The water to be higher in dissolved solids than the applied irrigation water.

(b) The distribution of various cations and anions to be different than in the applied water.

(c) The total salt load to be greater or less, depending upon whether there has been deposition or leaching.

(d) The water to contain little or no sediment or colloidal material.

(e) The nitrate content to be less than in the applied irrigation water if the irrigation water was initially high in nitrate and, conversely, the nitrate content to be greater if the applied irrigation water had little or none.

(f) A general reduction in phosphorus unless the applied irrigation water had little or no phosphorus.

(g) A reduction of all bio-degradable material such as detergents, etc.

(h) A general reduction of oxidizable organic substances.

(i) A reduction of pathogenic organisms and coliform bacteria.

Many other changes are also likely.

Drainage water from either source discussed above will have an effect upon the receiving water in proportion to respective discharges and the relative quality of the receiving water. The composite flow below the point of confluence may contain proportionately more or fewer undesirable constituents than originally.

Impact of Poor Water Quality on the Irrigation Farmer

The use of saline waters for irrigation imposes extra burdens on the irrigation farmer. Salinity generally reduces growth and yield. It may restrict production to the more tolerant crops. Generally, the farmer must apply an additional amount of water to maintain the salt balance at an acceptable level of soil salinity hence each unit of water has a lower value. Better drainage conditions may be required, and sometimes the adequacy of drainage cannot be controlled by an individual farmer, but requires group action. Outlets and collectors generally must be provided on a project or district basis to enable individual farmers to provide the necessary additional farm drainage. The farmer using low quality water may be restricted in his irrigation methods, or he may have to adopt special practices to obtain germination. Since the irrigation method must be suited to the crop grown, this may further restrict the crops that can be grown economically. Sprinkling may not be practical because of the accumulation of salts, especially chlorides, on the leaves, and the resulting leaf burn or defoliation.

In some instances, and where this is possible, the more saline water may have to be mixed with a water of better quality in order to use it for irrigation. In most cases, however, the farmer has no opportunity to dilute undesirable water and must use what is available. When a farmer has a well for supplemental supplies, but uses gravity supplies to the extent available, mixing the two may be feasible to produce an acceptable quality. Often groundwater is more saline than gravity supplies. It can be used to provide the required drainage by pumping it into the canal system and mixing it with the gravity supply. This practice provides adequate control of the water table (drainage), and appreciable additional water supply to several irrigation districts in California, including the very successful operations of the Turlock and Modesto Irrigation Districts.

The leaching required when using moderately saline waters may impose an additional burden in the form of a greater fertilizer requirement. Leaching salts from the soil also removes nutrients, especially nitrates. Sometimes, heavier than normal applications of phosphate fertilizers improve the production on saline or sodic soils. In general, the farmer often must practice special techniques to cope with the adverse effects of salt and other pollutants.

Principal Effect of Salinity

The worst effect of poor water quality is a lowered agricultural production. Reduced yields result when the total salinity of the soil solution in the root zone exceeds certain values (13). It must be emphasized that it is not the quality of the irrigation water per se, but the concentration of the salts in the root zone, that is important. The increased osmotic concentration of the soil solution inhibits entry of water into the root system and restricts growth and yield. Direct measurement of the salt concentration in the root zone is difficult, and usually not practical under field conditions. The standard procedure is to prepare a saturation extract (13) from a soil sample and to determine the electrical conductance (EC) of the extract. The salinity of the soil saturation extract is much less than the actual salinity of the soil solution, for the soil moisture ranges between field capacity and wilting percentage. The ratios depend on the relative values of wilting percentage, field capacity and saturation, and on the composition of the salts present. The use of saline waters for irrigation may be a principal cause of high soil salinity levels and result in an appreciable reduction in yield, which often goes unnoticed because salinity may not result in any distinct symptoms even though reduction in growth and yield may be significant.

In 1945, Magistad (16) published a review of the literature on plant growth and salinity relations, containing 362 references. A similar review, to bring the subject up-to-date, published by Hayward and Bernstein (17) in 1958, included 221 references. Many of these references stress the complex relationships between plant growth, soils, salinity, and sodic or alkali conditions.

Distribution and concentration of salts in the root zone

Since it is the salinity of the soil solution rather than that of the water applied that affects production, some knowledge of factors that affect the concentration and distribution of the salt in the root zone is important from the farmer's point of view. The more important of these factors are: adequacy of drainage from the soil profile; quality of irrigation water applied; ratio of the depth of water applied to the actual evapotranspiration; and the irrigation method.

Adequacy of drainage. Adequate drainage of the soil profile is essential to a permanent irrigation agriculture. Unless the excess water applied is removed from the soil, the water table will rise and the salt concentration will increase. The adequacy of drainage can best be judged by the depth of the water table below the ground surface. This is often greatly influenced by soil texture and topography.

When the water table is near the surface, less than four to six feet, there usually will be an appreciable fluctuation in water table depth between irrigations. Each irrigation will cause a rapid rise in the water table, followed by a period of decline which is due both to the removal of moisture from the root zone by evapotranspiration and the resulting upward movement of soil moisture from the saturated zone into the root zone, and to the removal of groundwater from the saturated zone by drainage, either natural or man-made. The water removed by the drainage carries with it the salt in solution, but the moisture removed by evapotranspiration leaves the salt in the soil in the form of increased concentration of the soil solution, and sometimes as precipitates of the less soluble salts of calcium and magnesium.

When drainage is impaired, the salt concentration in the root zone generally increases, and unless a salt balance can be established through better drainage, the salinity will increase to such a degree that no crops can be grown. Sometimes serious salinity problems result from poor drainage even when the irrigation water is of excellent quality (18). Adequate drainage is essential before soil salinity can be improved by leaching. Better drainage, with a lower water table and better control of the water table, is more important where the irrigation water is of poor quality than where it is of good quality. Increased costs for drainage may be a necessary burden on the irrigation farmer using low quality water.

Quality of irrigation water. Because of the concentrating effect of evapotranspiration, quality of irrigation water directly affects the concentration of salts in the root zone. For example, water with a conductance of only 100 µmhos would have to be concentrated to 1/20 of its volume, providing none of the salts precipitated, in order to reach a conductance of 2 mmhos, while water with a conductance of 1 mmhos would only have to be concentrated to half its volume to reach the same concentration in the soil. Actually, the difference would be greater than this. Water with a conductance of 100 µmhos would probably have a much higher percentage of calcium and bicarbonate ions than one with a conductance of 1 mmhos, and since some of these would precipitate on concentration, the water with an initial conductance of 100 µmhos might have to be reduced to 1/40 or 1/50 of its original volume to reach a conductance level of 2 mmhos. Examples were cited in a discussion by Christiansen and Thorne (19). This means that the leaching requirement, the excess water that must be applied in addition to the evapotranspiration to maintain a given level of soil salinity, increases faster than the salinity of the water. This imposes an added burden on the farmer.

The term "quality of irrigation water" implies other factors besides salt concentration, such as the composition of the salts, especially with respect to the presence and percentage of sodium, presence of residual sodium carbonate, and toxic substances such as boron and/or pesticides. Several schemes have been proposed for evaluating, or classifying, waters with respect to their use for irrigation. None of them completely satisfy all requirements and should be used only as a tentative guide. For permeable soils with excellent drainage, and where adequate applications are made to insure leaching, water of poor quality may result in greater production than would much better water where drainage is impaired.

The amount, or percentage, of sodium in the water is very important. Water with a fairly high sodium percentage, say greater than 50 percent, will generally increase in sodium percentage upon concentration in the soil to levels that produce relatively high exchangeable sodium percentages in the soil. Soils that become high in exchangeable sodium are more difficult to leach, for two reasons: they tend to disperse, with a resulting reduction in permeability when leaching is attempted, and they may require the addition of an amendment, such as gypsum, to replace the exchangeable sodium. Soils that contain more than 15 percent exchangeable sodium are classified as sodic (13).

The presence of toxic substances such as boron, or possibly a pesticide that degrades slowly, may limit the usefulness and value of poor quality water even more than do normal salts. Many crops are very sensitive to boron and concentrations of more than 1 ppm in the irrigation water may restrict production to the more tolerant crops.

The amount and frequency of water applied. The amount of water applied and the degree of leaching accomplished in the root zone have a major effect on the concentration and composition of the salts left in the root zone. Even though extra water might be available to the farmer, the drainage conditions may limit the amount of water that can be used effectively for leaching.

In 1943, Wilcox and Christiansen (unpublished data) found well water being used for irrigation in the Welltón-Mohawk area in southern Arizona with a total salt content of more than 10,000 mg/l (EC > 15 mmhos/cm). Because of excellent drainage and soil conditions, saturation extracts from soil samples obtained were not as high as for many soils where waters of much lower salt content are used. The relatively low salt content in the root zone was attributed to the large amount of water used for irrigation and to the excellent drainage.

The amount of water that can be applied by a farmer is frequently limited by his water right or by the available supply. Sometimes, however, he can take advantage of available supplies during the non-irrigation season to thoroughly leach his soil, providing drainage conditions permit. Where the farmer has control of his water supply, such as when he obtains the water from his private well, he can better manage his soils by a proper degree of leaching, and can offset to a considerable extent the detrimental effects of salinity, especially where he is not plagued by lack of drainage. Areas that depend on groundwater for all, or an appreciable part of, the water supply often are free from drainage problems, and can be leached more effectively because of the low water tables. Generally, however, pumped water is more costly than gravity supplies, and this also is an added burden to the farmer. Leaching may be partly or completely taken care of by seasonal rainfall, although irrigation may be required during the dry season.

Irrigation method. The irrigation method used has an appreciable effect on the resulting concentration and distribution of salts in the soil profile. Furrow irrigation, for example, is not as effective for leaching and may result in high concentrations of salt near the surface of the beds between the furrows. Rotation of crops from those conventionally irrigated by furrows, such as corn, cotton and vegetables, to alfalfa or other crops that can be irrigated by flooding (border strips or basins) is an effective way to prevent continuous buildup of salts in the soil profile. For high salt waters, the furrow method is usually less satisfactory. Salt-tolerant crops that can be flooded should be grown when possible.

Sprinkling is also a good method to provide leaching when adequate amounts of water are applied. Sometimes, however, because of a user's ability to spread water effectively in small applications by sprinkling, he may not apply an adequate amount of water, and there may be a buildup of salts even though drainage is entirely adequate.

There are other limitations in the use of sprinkling with water of poor quality. Salts may precipitate on the leaves of crops and produce leaf burn and defoliation. This is especially true where "under tree" sprinklers are used in orchards. Leaves on the lower branches are often wet only very lightly and salts precipitate and accumulate on these leaves because they are never thoroughly washed by the sprinklers. On field crops less trouble is experienced and, except for relatively saline waters, sprinkling should be satisfactory because the salts are thoroughly washed from the leaves.

Effect on seed germination

The salinity effect on plant growth is often more pronounced on germination and during the seedling stage. Where salts have accumulated in the soil near the surface as a result of a high water table, it may be difficult to obtain satisfactory germination without pre-irrigation which temporarily reduces the salt content of the soil near the surface. Unfortunately, under conditions of poor drainage, heavy applications before planting will cause an additional rise in the water table and may do more harm than good.

Under some saline soil conditions, satisfactory germination of certain row crops can be obtained by planting along the edge of the furrow that has been pre-irrigated instead of in the top of the bed where the salt concentration is greater. This is a standard practice in some areas where there is appreciable salinity and where the water supply is not of the best quality.

Other farm management practices to offset effects of salinity

In addition to the management practices that have been suggested to offset some of the detrimental effects of salinity and/or sodic conditions, such as increased water use for leaching, the need for better drainage, and proper irrigation methods, there are some additional practices that are helpful under certain conditions.

Where soils have developed low infiltration rates as a result of an increase in exchangeable sodium, or because of detrimental management practices such as excessive cultivation, it is especially important for the farmer to recognize the problem, and to do all possible to correct the difficulty. Some silt soils are readily dispersed, and develop infiltration problems under ordinary management practices. This is especially true under furrow irrigation where the amount of water applied is not adequate because of low infiltration rates. The problem becomes more intensified with time as a result of a buildup in salinity, and especially in exchangeable sodium.

A problem of this kind was experienced in the Coachella Valley in California (20) where a date garden had been irrigated by the furrow method for a number of years. Production was quite variable and unsatisfactory. A study indicated that the infiltration rates were extremely low, possibly as a result of the application of low salinity-high sodium water, and under the practices being followed, salts were accumulating in the soil because no leaching occurred. Applications of gypsum and heavy applications of organic matter increased infiltration rates, but more effective drying of the soil in the early spring before the hot weather set in was even more effective. The practice of permitting effective drying of the soil between irrigations improved soil aggregation and infiltration rates. Basin irrigation was required to obtain adequate applications and penetration of the water.

Where infiltration rates are low, and effective penetration of water into the soil is a problem, excessive cultivation of the soil should be avoided, especially when the soil is wet, and the soil should be allowed to dry periodically to a point where the crop shows visible stress. Improved soil aggregation is difficult to obtain without the drying action.

Crop rotation, which includes those that improve soil aggregate stability or structure, should be practiced where it proves effective in offsetting the effects of poor water quality. Soils with a poor physical condition, which may have resulted from an increase in exchangeable sodium, are sticky and plastic when wet. They develop large cracks with very hard clods when they dry. Often it is very difficult to achieve satisfactory germination of seeds in such soils, and cultivation must be very timely to prevent detrimental results. A change to sprinkler irrigation, with a low application rate, may prove effective in decreasing the physical degradation of the soil caused by saturating the soil during flood irrigation.

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THE QUALITY PROBLEM

Scope and Magnitude

In one sense, the scope of the problem of return flow and degradation of water quality from irrigation is as large as the scope of irrigation itself. All irrigation water contains dissolved minerals (salts). When applied to soils, some of these salts will accumulate in the soil unless leached from it by excess irrigation water or by natural precipitation. A permanent productive agriculture under irrigation is basically dependent upon a salt balance in the root zone of the crops grown (12, 13, 14, 15, 21, 22).

The concentration of the salt in the soil solution will usually be in the range of four to 10 times the concentration of the irrigation water; hence, the solution draining from the soil profile is usually much higher in salt content than the water applied. Where the drainage from the root zone is impeded by a high water table, the concentration of the soil solution may be 40 to 80 times the concentration of the irrigation water (21).

Fortunately, the concentration of salt in many irrigation waters is so low that the leachate under normal irrigation practice is much less concentrated than theoretically permissible, and when returned to the stream, or the groundwater body, the effect on the quality of the resulting water is often negligible. The scope of the problem of return flow is, therefore, limited from a practicable standpoint to those areas and conditions where water quality becomes so degraded that further use of the water constitutes a nuisance or hazard.

Acreage affected by salinity

Irrigated soils are scattered throughout most of the United States. The major areas are in the seventeen western states. Many of the irrigated soils contain enough salt to be classed as saline or have enough exchangeable sodium to be sodic. An estimate of acreage of salt-affected soils is given in Table 1. California, with the greatest acreage of irrigation land, also has the most acreage affected by salt. From such soils may come the increase in salt in the return flow, over and above the concentrating effect of evapotranspiration.

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Table 1. Status and extent of saline and sodic areas in the seventeen western states and Hawaii 1960.[1]

State	Area reported	Total acreage[2]	Salt-free		Saline-all classes	
			Acres	%	Acres	%
Arizona	Statewide	1,565,000	1,166,170	74.5	398.830	25.5
California	Statewide	11,500,000	7,755,049	67.4	3,744,951	32.6
Colorado	Statewide	2,811,532	1,829,704	65.1	981,828	34.9
Hawaii	7 areas	117,418	71,868	61.2	45,550	38.8
Idaho	All but 3 counties	1,880,063	1,627,118	86.5	252,945	13.5
Kansas	Statewide	421,545	319,215	75.7	102,330	24.3
Montana	4 areas	1,242,728[3]	1,045,057	84.1	197,671	15.9
Nebraska	Statewide	1,218,385	928,385	76.2	290,000	23.8
Nevada	Statewide	1,121,916	646,316	57.6	475,600	42.4
New Mexico	Statewide	850,000	659,000	77.5	191,000	22.5
North Dakota	6 areas	2,636,500[3]	1,819,870	69.0	816,630	31.0
Oklahoma	Statewide	826,650	632,900	76.6	193,750	23.4
Oregon	Statewide	1,490,394	1,387,033	93.1	103,361	6.9
South Dakota	Statewide	1,697,974	501,708	29.5	1,196,266	70.5
Texas	4 areas	2,198,950	1,923,096	87.5	275,854	12.5
Utah	7 areas	1,390,222	877,440	61.1	512,782	36.9
Washington	23 counties and the Columbia Basin	2,221,484	1,955,230	88.0	266,254	12.0
Wyoming	Statewide	1,261,132	981,429	77.8	279,703	22.2
TOTAL		36,451,893	26,126,588	71.6	10,325,305	28.4

[1] Unpublished data from the U. S. Salinity Laboratory

[2] Irrigable

[3] Arable

Areas adversely affected by return flow

Areas most adversely affected by irrigation return flow are those in the lower reaches of the larger river systems of the southwestern United States: in the lower basin of the Colorado River, the Gila and Salt Rivers of Arizona, the Rio Grande in New Mexico and Texas, the San Joaquin River in California, and similar streams. In all of these river basins there is a progressive deterioration in water quality as it flows downstream. In many instances, quality of water in the headwater tributaries is excellent: low in total dissolved solids, and usually with low sodium to calcium ratios. As the total concentration of salts increases downstream, there is also a gradual increase in the sodium percentage due to precipitation of low solubility calcium salts in the soil and sometimes because of cation exchange reactions. It is not, however, until the total salt concentration, and/or the sodium percentage, reaches a level where management of the soil, or loss of productivity, becomes a problem that much thought is given to the problem of degradation of water quality as a result of return flow. More commonly, the problems associated with drainage and with maintaining a favorable salt balance in irrigated areas have been given the most attention, but not always before the effects of water logging and salinity have become acute in the lower portions of the irrigated area. In some locations, natural drainage of the irrigated lands has become adequate; the groundwater table has remained well below the ground surface, and the leachate has moved vertically through the soil profile to the groundwater body, thence laterally toward the stream channel where it augments the stream flow and usually degrades the quality.

The greatest effect on quality is during the periods of low flow in the streams. As the water resources are more fully developed, and upstream reservoirs are constructed to even out the flow of the streams, there is a stabilizing effect on fluctuations in salinity of the waters. For example, before construction of Hoover Dam on the Colorado River, there were wide fluctuations in both stream flow and water quality in the lower reaches of the river. Now, with storage at Flaming Gorge Reservoir, Lake Powell, Lake Mead and on tributary streams in Colorado and New Mexico, the flow has been regulated to meet the demand, and the quality stabilized to a salinity level somewhat above the weighted mean value prior to development, but well below the levels reached during the late summer before the construction of Hoover Dam. Hill (23) has estimated that the salt concentration of the Colorado River on Lake Havasu, which averaged about 10.75 milliequivalents per liter (me/l) for the 1940-1960 period, may increase to about 15 me/l with full development of the upper basin.

In other areas, such as the Salt River Valley in Arizona, the San Joaquin Valley of California, and the high plains area of Texas and New Mexico, only a small part of the leachate from the irrigated lands has rejoined the river systems. Most of it has rejoined the underlying groundwater body. Because of the large storage capacity of some of the underground reservoirs, and the kind of geologic formations present, the effects of this natural downward drainage of the leachate has been hardly noticeable on changes in groundwater quality. In other areas, however, where the underground storage capacity is limited, and/or the salinity of the groundwater has been higher, the recirculation of groundwater has rapidly increased the salinity of the water (24). In many areas, where groundwater has been of good to fair quality, there is a lack of long-time records from which the magnitude of changes in groundwater quality can be assessed.

Salt balance and quantities of salt involved

To illustrate the magnitude of the problems of salinity of irrigation waters, of salt balance, and of drainage requirements of irrigated areas, one can cite data for the Imperial Irrigation District in southern California, where records have been kept since 1944 (25). Imperial Valley was a barren desert in 1900. With the construction of the diversion works on the Colorado River in 1901, water was first brought into the valley. In 1905 the headworks on the Colorado River were washed away by a large flood, and the river flowed uncontrolled into the valley for two years before being brought under control. This flood formed the Alamo and New Rivers, and the Salton Sea.

Problems of silt and salt plagued the valley for many years. The silt problem diminished with the completion of Hoover Dam in 1936, but the salinity and drainage problems continued to increase. In 1940, the U. S. Soil Conservation Service began an investigation of drainage and salinity problems. A salt balance study was undertaken in 1943 when about 500 miles of subsurface tile lines had been installed, supplementing more than 1, 000 miles of open collector drains. As the number of tiled acres increased, the salt balance improved as indicated in Table 2.

These data indicate that during the 24-year period a total of more than 46 million tons more salt left the area than came in with the irrigation water. In this instance the return flow of saline water was not detrimental to downstream areas, as there were no diversions of this water for irrigation or other purposes. All of it entered the Salton Sea, where the water evaporates.

Table 2. Drainage and salt balance in the Imperial Irrigation District[1] (25).

Year	Tile drainage total installed		Salt balance		Net balance
	miles	acres	inflow 1000 tons	outflow 1000 tons	
1943	536	-	2,158	1,999	-159
1947	1,109	53,640	2,795	2,431	-364
1949	1,959	92,530	2,653	2,798	+145
1953	4,242	177,150	3,348	3,758	+410
1957	6,340	232,760	3,789	3,993	+204
1961	9,029	286,634	3,330	3,573	+243
1963	10,405	308,248	3,379	4,050	+671
1966	12,662	335,547	3,650	4,149	+499
1966 (excluding Mexico)			3,384	3,921	(+537)
TOTAL net balance for all 24 years 1943-1966					46,247

[1] Including small amount of water and salt from Mexico

In 1966, Colorado River water entering the district had an average salt content of about 900 ppm, or 1.20 tons per acre foot. The salt balance in terms of constituents for 1966 is given in Table 3.

Table 3 clearly indicates a phenomenon that usually takes place in an irrigated area. There was precipitation and deposition of 427,668 tons of Ca, HCO_3, and SO_4 ions in the area, and a net outflow of 944,594 tons of Na, K, and Cl ions. The composition of the water changed accordingly as recorded in Table 4.

San Joaquin Valley drainage and salt balance problems

In recent years, major concern has been voiced regarding problems of drainage, return flow and salt balance in the San Joaquin Valley of California (26, 27, 28). This valley contains more than 4.5 million acres of irrigated land, or more than half of the total irrigated area of the state. The valley is composed of two major basins, the Tulare Lake Basin in the southern end, and the San Joaquin Basin to the north. Tulare Lake Basin does not

Table 3. Salt balance constituents, 1966[1] (25).

Ion	Inflow tons	Outflow tons	Net tons
Cations:			
Ca	403,593	311,395	-92,198
Mg	136,264	156,024	+19,760
Na+K	564,231	848,172	+283,941
Total	1,104,088	1,315,591	+211,503
Anions:			
HCO_3	349,625	168,171	-181,454
SO_4	1,332,132	1,178,116	-154,016
Cl	598,785	1,259,483	+660,653
Total	2,280,542	2,605,725	+325,183
TOTAL salt	3,384,626	3,921,316	+536,690

[1] Excluding water and salt from Mexico.

Table 4. Comparative concentration of irrigation and drainage waters, Imperial Irrigation District, 1966 (25).

Ion	Inflow		Outflow		Ratio Outflow/Inflow	
	t/af.	me/l	t/af.	me/l	t/af.	me/l
Cations:						
Ca	0.143	5.24	0.310	11.38	2.17	2.17
Mg	0.048	2.06	0.155	9.38	3.23	4.55
Na+K	0.200	5.84[1]	0.844	25.21[1]	4.22	4.32[1]
Total	0.392	13.14[1]	1.309	45.97[1]	3.34	3.50[1]
Anions:						
HCO_3	0.124	1.49	0.167	2.02	1.35	1.36
SO_4	0.473	7.25	1.173	17.95	2.48	2.48
Cl	0.212	4.40	1.254	26.00	5.92	5.91
Total	0.809	13.14	2.594	45.97	3.21	3.50
TOTAL salt	1.201		3.903		3.25	
SAR[2]	3.05		7.85		2.57	
Class.[3]	C3-S1		C4-S3			
EC-mmhos/25°	1.30		4.30		3.30	

[1] Estimated from total anions.

[2] Sodium adsorption ratio.

[3] U. S. Salinity Laboratory classification.

have surface drainage into the San Joaquin Basin, and because of the lowered groundwater levels due to pumping for irrigation, it has no subsurface drainage.

A large part of the valley is irrigated from groundwater, either for the full supply, or to supplement surface water supplies. In some instances, as in the Turlock and Modesto Irrigation Districts, the groundwater is pumped primarily as a means of water table control (drainage), but the pumped water is discharged back into the irrigation canals and reused. Some years nearly a third of the water distributed to farmers is from the pumping operations. The balanced groundwater and surface water development has completely eliminated the need of other subsurface drainage for most of the irrigated area, and has provided an economical source of supplemental water supply. The groundwater quality for most of the area is good, although it becomes progressively more saline from east to west.

A larger percentage of the Tulare Lake Basin is irrigated with groundwater, and this has caused an overdraft on groundwater supplies, estimated at more than two million acre feet per year. In some places wells are more than 2,000 feet deep, and pumping lifts are from 400 to 600 feet (27).

The total groundwater storage capacity of the valley, to a depth of 200 feet, has been estimated at 93 million acre feet, or nine times the storage capacity of the existing and proposed surface reservoirs of the valley. More than half of the water used for irrigation in the valley is pumped from the groundwater (27). The total value of agricultural production in the valley in 1963 was estimated at more than $1.7 billion with Fresno, Kern, and Tulare counties ranking 1, 2, and 3 in value of agricultural production in the United States.

To alleviate the groundwater overdraft, and permit more complete development of the irrigable area, water has been imported from the Sacramento River Basin through the combined efforts of the U. S. Bureau of Reclamation and the State of California. The most recent area to be developed is the San Luis Project on the west side of the valley. The subsoils in this area are less permeable, and experience has shown that subsurface drains are required. Because of the high salt content of this drainage water, it cannot be returned to the San Joaquin River for disposal to the San Francisco Bay area, but will have to be transported there by the proposed San Luis Drain, or by a larger drain, the San Joaquin Master Drain (21, 26, 28), designed to provide for the eventual needs of the entire valley. The latest available information (29) is that the U. S. Bureau of Reclamation is proceeding with construction of the San Luis Drain, and that the San Joaquin Master Drain will be deferred.

The San Joaquin Valley drainage investigations (26) indicate that eventually there will be more than 1.5 million acres of irrigated land in need of drainage, and that by the year 2000, the required drainage outflow will approximate one-half million acre feet per year. The salt concentration of this drainage outflow is expected to reach a maximum of about 6,500 ppm as new irrigated areas are brought into production, then decrease within a 50-year period to a level of about 2,500 ppm. This would indicate that such a master drain might transport as much as two million tons of salt annually. This is about half of the total amount of salt estimated to be coming into the valley annually from all sources (29). Where there is a large overdraft on the groundwater, as in the Tulare Lake Basin, and no natural outflow of groundwater, a salt balance may never be achieved, and as the groundwater in various parts of the area becomes too salty for further use, the irrigated area may decrease unless surface supplies of better quality can be substituted, and adequate drainage provided.

Irrigation water and return flow in the Yakima Valley, Washington

A comparison of the irrigation water quality and return flow in the Yakima Valley, Washington, was made by Sylvester and Seabloom (30). In this instance, the irrigation water had a very low salt content (EC = 83 μmhos). Analyses were made of the return flow from seven subsurface (tile) drains, and five open drains near their exit. The water in these open drains presumably included drainage water from tile drains and waste water from canals and field runoff. A condensation of the results of the analyses and conversion of the units to me/l is given in Table 5.

An estimate of the water and salt balance for the valley indicated that the total annual diversion was 6.6 acre feet per acre, and the return flow was 4.0 acre feet per acre, leaving 2.6 acre feet per acre as the evapotranspiration. Computed from the average composition, according to the analyses, the inflow and outflow of salt from the 385,280 acres of irrigated land is shown in Table 6.

Tables 5 and 6 are interesting in that they illustrate changes that occur when irrigated waters have a very low salt content, but with about the same amount of HCO_3^- as Ca^{++} plus Mg^{++}. In this

Table 5. Comparison of irrigation water and drainage water, Yakima Valley, Washington (30).

Constituent	Applied Water[1]		Tile Drains[2]		Open Drains[1]	
	me/l	%	me/l	%	me/l	%
Cations:						
Ca	0.50	44	2.24	40	1.54	41
Mg	0.41	36	1.62	29	0.99	26
Na	0.18	16	1.62	29	1.13	30
K	0.04	4	.11	2	.13	3
Anions:						
HCO_3	0.92	86	4.31	78	2.76	73
Cl	0.03	3	0.33	6	0.22	6
SO_4	0.11	10	0.84	15	0.77	20
NO_3	0.01	1	0.06	1	0.03	1
EC µmhos[3]	83.0		420.0		283.0	
Temperature °C	16.0		13.3		17.9	
Oxygen, mg/l	10.2		6.8		9.0	
pH	8.1		7.7		8.2	
COD, mg/l[4]	7.0		9.0		10.0	
Hrdness as $CaCO_3$	46.0		186.0		121.0	
Turbidity units	37.0		12.0		130.0	
Total PO_4, mg/l	0.32		0.86		0.83	
Coliforms per 100 ml	1,070.0		103.0		10,600.0	

[1] Average for 7 stations.

[2] Average for 5 stations

[3] Electrical conductance in µmhos per cm at 25 °C.

[4] Chemical oxygen demand.

Table 6. Salt balance, Yakima Valley (30).

Constituent	Inflow tons	Outflow tons	Net tons	Ratio O/I
Cations:				
Ca	33,600	73,000	+ 39,400	2.17
Mg	16,900	33,400	+ 16,500	1.97
Na	13,700	60,500	+ 46,800	4.42
K	4,700	7,800	+ 3,100	1.66
Anions:				
HCO_3	190,000	430,000	+240,000	2.26
Cl	3,400	22,000	+ 18,600	6.48
SO_4	18,200	65,000	+ 46,800	3.57
NO_3	3,600	16,300	+ 12,700	4.53
TOTALS	281,100	708,000	+426,900	2.52

instance it is understood, but not mentioned by the authors, that before the present drainage facilities were installed large areas of irrigated land were water-logged and saline. Apparently, under present conditions, the outflow of salts greatly exceeds the inflow. The effluent from the tile drain is, however, not highly saline and could be used for irrigation without dilution. The ratio of outflow to inflow for all ions exceeds the ratio of the inflow of water to the outflow, which was 1.65. This situation occurs where lands that have become saline because of inadequate drainage are being reclaimed after the construction of such facilities, and where new lands with soils containing large amounts of soluble minerals are first brought under irrigation and adequate drainage is provided.

Salt balance and return flow to groundwater basin

Problems of return flow and salt balance for groundwater basins are very complicated and depend on specific conditions, so that only a very general discussion appears warranted. As previously mentioned, reliable data from which the rate of increase in salinity of the water can be determined, and from which predictions for the future can be made, are limited. It would appear that inevitably, in any groundwater basin that is pumped to the extent that there is no natural subsurface outflow, the water quality would gradually become degraded by the amount of salt in the recharge flow whether from surface or subsurface sources. The rate of degradation would depend on many factors, such as the capacity of the groundwater reservoir as compared with the annual draft, the general quality of the groundwater and the depth of the producing aquifers and presence or absence of confining strata of low permeability above the aquifers. The rate of degradation would probably be exponential with respect to time, rather than linear.

The difficulty in arriving at any generalized rate of increase in salinity of groundwater is illustrated by Huffman (28 - closure) who says:

> It is difficult to estimate when, on the average, the groundwater of the southern part of the San Joaquin Valley will no longer be suitable for use without being diluted. The unconfined aquifers will go first. In some places, high concentrations have already appeared in pumped water and the wells are now abandoned. . .
>
> The Department has studied the idea of increasing concentrations of salts in the groundwater, with time, as sampled from key wells. It initiated its groundwater quality data program in 1952, although records of groundwater qualities have been obtained since the mid 1930's. The large variability of groundwater quality in the valley precludes any generalized statement of quality trends.

Huffman showed that five of the seven wells reported had increases in salinity ranging from 1.4 to 9.6 percent per year. One well showed an increase from 964 to 2,050 µmhos in a two-year period, a gain of 46 percent per year. The other well showed a decrease in salinity from 564 to 490 µmhos in two years, or 7.4 percent per year. No explanation for such a decrease was given.

Water Quality Requirements for Crops

Pollutants in irrigation water can adversely affect crop growth and quality; they affect the soil, which indirectly affects the crop, and they affect the consumer of the crop. Some pollutants do not actually impair growth or impart harmful constituents to the crop, yet may affect the acceptability of the crop to man or animal.

Plant response

Crops may be adversely affected by high concentrations of salts due to development of abnormally high osmotic pressures in the soil solution, or by the presence of toxic substances in the soil water. The crops may be indirectly affected through the influence of irrigation water on the soil. Such a condition is developed when the proportion of sodium in the water is proportionally greater than calcium plus magnesium and the adsorbed sodium causes dispersion of the clay fraction of the soil. This results in land that tends to form surface crusts and is impermeable to air and water.

There are other quality factors that adversely affect plant growth, such as temperature extremes, nutrient imbalance, and lack of oxygen induced by oxidizable organic matter in the water.

Osmotic effects

The total concentration of soluble salts is probably the most significant criterion of irrigation water quality. This is related to salinity in the soil solution, which is further concentrated by evaporation and transpiration. Plant growth may be seriously reduced or even prevented because the salts increase the osmotic pressure of the soil solution, making it difficult for plants to obtain water, thus inducing physiological drought.

Electrical conductivities of the water or soil solutions are directly correlated with osmotic pressures. For this reason easily determined conductivity measurements can be substituted for tedious osmotic concentration measurements when determining the salt content of soil or water. Conductivity is usually expressed as millimhos per centimeter for soil solutions and as micromhos per centimeter for water.

Phyotoxic substances

Many substances can occur in irrigation waters in concentrations which cause direct toxic damage to plants. Included are boron compounds and chlorides, which occur in natural waters and trace elements, heavy metals, and pesticides which are artificially applied or washed out of the atmosphere. Plant pesticides may be spread by irrigation, especially by sprinkler irrigation. Chlorides are not particularly toxic to most crops, but certain crops, such as citrus, stone fruits, and almonds, are sensitive. Chloride damage often may not be distinguished from osmotic effects. Damage to plants can result from absorption of chlorides from salty water applied through a sprinkler system. High concentration of bicarbonate ions may induce iron chlorosis in sensitive plants. Tolerance limits are difficult to establish because calcium salts in the water will reduce bicarbonate ion concentration by the precipitation of calcium carbonate. Considerable information is available on the levels of concentration of boron which will be toxic to different plants. In contrast, very little is known about the levels of other substances harmful to different crops or the mode of damage, and, therefore, establishment of meaningful tolerance limits of the different materials for the different plant species is difficult. The amount of pollutants in the soil may be more critical than the amount in the water.

Nutritional imbalance

Most crops require a relatively well balanced nutrient content in the soil solution. Salty irrigation water may significantly upset the balance if the composition and concentration are unfavorable. High concentrations of sodium salts may cause a deficiency in calcium and magnesium. High proportions of calcium salts in the water may prevent plants from obtaining enough potassium. The effect of different salts and varying concentrations on the magnitude of nutritional imbalance induced is difficult to evaluate. Except for a few sensitive crops, or with waters of high salinity, there is no evidence of a serious problem of nutritional imbalance in irrigation agriculture.

Soil physical properties

The sodium content of irrigation water influences the permeability of the soil. Soils with a high percentage of exchangeable sodium have physical properties generally unfavorable for water intake, drainage, and plant growth. This condition may be induced or aggravated when there is an unfavorable ratio of sodium to calcium plus magnesium in the water. Permeability of the soils, particularly the clay soils, is reduced because of increased dispersion. Such soils tend to puddle easily when wet and form hard crusts and clods when dry. Waters, although relatively low in total soluble salt, may induce adverse physical effects due to adsorbed sodium. Conversely, the salt content may be high enough to cause adverse osmotic effects with no particular deterioration of the physical properties.

Presently accepted criteria for irrigation

Differences in water quality for irrigation have been recognized by users of the water and by scientists. Schofield (31) in 1936 established a system for rating waters which ranged from excellent to unsuitable. A number of later systems have been proposed which were largely empirical. Most of the systems have recognized the adverse osmotic effects of soluble salts, the unique effects of sodium on the soil, the direct and indirect effects of bicarbonate ions, and the specific toxic effects of boron. Current systems attempt to indicate the effects water will have on the soils and crops and also recognize pollutants that normally do not occur in natural waters.

Recently, a National Technical Advisory Committee to the Secretary of the Interior (3) reviewed the variously proposed criteria and classifications. This committee recognized the interacting effects of soil, climate, and plants. It acknowledged that no set of criteria could be used to evaluate all water quality characteristics for irrigation, and suggested guidelines or tolerance limits for salinity, trace elements, herbicides, and sodium hazard. Some of these guides are reproduced as Tables 7, 8, 9, and 10. The committee cautioned that the values suggested should be used in combination with the discussions in the text of the report. Besides providing guidelines on maximum permissible levels, Table 10 shows the variety of substances involved and sources of origin of pesticide materials.

Table 7. Suggested guidelines for salinity in irrigation water (3).

Crop response	TDS mg/l	EC[1] mmhos/cm
Water for which no detrimental effects will usually be noticed	<500	<0.75
Water which can have detrimental effects on sensitive crops	500-1000	0.75-1.50
Water that may have adverse effects on many crops and requiring careful management practices	1000-2000	1.50-3.00
Water that can be used for salt-tolerant plants on permeable soils with careful management practices	2000-5000	3.00-7.50

[1] Electrical conductivity.

Table 8. Trace element tolerances for irrigation waters (3).

Element	For water used continuously on all soils mg/l	For short-term use on fine textured soils only mg/l
Aluminum	1.0	20.0
Arsenic	1.0	10.0
Beryllium	0.5	1.0
Boron	0.75	2.0
Cadmium	0.005	0.05
Chromium	5.0	20.0
Cobalt	0.2	10.0
Copper	0.2	5.0
Fluorine	[1]	[1]
Iron	[1]	[1]
Lead	5.0	20.0
Lithium	5.0	5.0
Manganese	2.0	20.0
Molybdenum	0.005	0.05
Nickel	0.5	2.0
Selenium	0.05	0.05
Tin	[1]	[1]
Tungsten	[1]	[1]
Vanadium	10.0	10.0
Zinc	5.0	10.0

[1] See text of original.

Table 9. Levels of herbicides in irrigation water at which crop injury has been observed[1] (3).

Herbicide	Crop injury threshold in irrigation water mg/l
Acrolein	Flood or furrow: beans-60, corn-60, cotton-80, soybeans-20, sugar beets-60. Sprinkler: corn-60, soybeans-15, sugar beets-15.
Aromatic solvents (xylene)	Alfalfa->1,600, beans-1,200, carrots-1,600, corn-3,000, cotton-1,600, grain sorghum->800, oats-2,400, potatoes-1,300, wheat->1,200.
Copper sulfate	Apparently, above concentrations used for weed control.
Amitrole-T	Beets (rutabaga)->3.5, corn->3.5.
Dalapon	Beets->7.0, corn-< 0.35.
Dequat	Beans-5.0, corn 125.0.
Endothall Na and K salts	Corn-25, field beans-< 1.0, alfalfa->10.0.
Dimethylamines	Corn->25, soybeans->25, sugar beets-25.
2,4-D	Field beans->3.5< 10, grapes-0.7-1.5, sugar beets-3.5.
Dichlobenil	Alfalfa-10, corn->10, soybeans-1.0, sugar beets-1.0-10.
Fenac	Alfalfa-1.0, corn-10, soybeans-0.1, sugar beets-0.1-10.
Picloram	Corn->10, field beans-0.1, sugar beets-< 1.0.

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[1] Data submitted by crops research division, ARS, USDA (unpublished).

Note: Where the symbol ">" is used, the concentrations in water cause no injury. Data are for furrow irrigation unless otherwise specified.

Table 10. Levels of herbicides in irrigation waters (3).

Herbicide	Site of use	Type of formulation	Treatment rate	Likely concentration in irrigation water reaching crop or field	Crop injury threshold in irrigation water (mg/l)[2]	Remarks
Acrolein	In water from cylinders under nitrogen gas pressure.	Soluble liquid	15 mg/lX4 hours.	10 to 0.1 mg/l	Flood or furrow beans-60, corn-60, cotton-80, soybeans-20, sugar beets-60.	Canals up to 200 cfs concentration reduced to minimum in 10 to 20 miles.
			0.6 mg/lX8 hours.	0.4 to 0.02 mg/l	Sprinkler: corn-60, soybeans-15, sugar beets-15.	Canals, 200 to 500 cfs concentration reduced to minimum in 20 to 30 miles.
			0.1 mg/lX48 hours.	0.05 to 0.1 mg/l		Canals 1,000 cfs and larger concentration to minimum in 30 to 50 miles.
Aromatic solvents (xylene).	Emulsified in flowing water.	Emulsifiable liquid.	6-10 gal/cfs in 30-60 minimum (300-750 mg/l).	700 mg/l or less	Alfalfa->1,600, beans-1,200, carrots-1,600, corn-3,000, cotton-1,600, grain sorghum->800, oats-2,400, potatoes-1,300, wheat->1,200.	Concentration reduced rapidly from point of application within 2 to 6 miles and almost completely in 6 to 10 miles.
Copper sulfate	In flowing water canals or in reservoirs.	Coarse pentahydrate crystals.	0.5 to 3.0 mg/l (continuous). 1/3 to 1 lb/cfs (slug).	0.8 to 0.04 mg/l in 10 miles. 9.0 to 0.08 mg/l in 10 to 20 miles.	Apparently above concentrations used for weed control.	Concentration reduced more rapidly with distance from slug applications.
Amitrol-T	On bank weeds along irrigation canals and on cattail in drain canals.	Foliage spray	6 to 16 lb/A	Usually less than 0.1 mg/l.[3]	Beets (Rutabaga)->3.5, corn->3.5.	Registered for use only in drain canals and marshes, but actually used for control of bank weeds along western irrigation canals.
Dalapon	do	Foliage	15 to 30 lb/A	Usually less than 0.5 mg/l.[3]	Beets->7.0, corn-<0.35.	Same as amitrol-T.
Diquat	In water or over surface of canals and reservoirs.	Liquid	3-5 mg/l or 1-1.5 lb/A.	Usually less than 0.1 mg/l.	Beans-5.0, corn-125.0	Diquat used in Florida for control of submersed weeds and floating weeds. Do not use for 10 days. Not used in western irrigation systems.
Diuron	On bottoms and banks of small canals when no water is in canal.	Wettable powder suspension sprayed	64 lb/A	Below crop injury threshold.	No data	Used mostly in small farm ditches with intermittent water flow.
Monuron	Same as for diuron	Same as for diuron.	64 lb/A	do	do	Same as for diuron except first water through canal after treatment not used for irrigation.
Endothal Na and K salts.	In ponds and reservoirs mostly in Eastern States.	Liquid or granule.	1-4 mg/l	Probably little or none after waiting period.	Corn-25, field beans-1.0, alfalfa->10.0.	Must wait 7 days after treatment before using water for irrigation or domenstic purposes.
Dimethylamines	In water control canals in Florida. Promising use in western canals.	Liquid	0.5-2.5 mg/l	Same as for Na and K salts.	Corn->25, soybeans->25, sugar beets-25	Wait for 7 to 25 days (depending on concentration) after treatment before using water.
2,4-D	Weeds along canal banks.	Liquid spray	1 to 4 lb/A usually as amine.	3.0 to 1.0 µg/l, 2 to 10 miles below treatment.	Field beans->3.5, <10. Grapes-0.7-1.5.	Registered precaution. Do not contaminate water to be used for irrigation.
	Floating and emersed weeds in southern canals.	do	do	0.1 mg/l or less to none in 3 weeks.	Sugar beets-3.5	A minimum waiting period of 3 weeks before using treated water for irrigation.
Silvex	Phreatophytes on floodways, along canals, reservoirs, and streams.	Liquid spray as ester.	2 to 4 lb/A	No data. Probably less than 0.1 mg/l.	No data	Silvex registered only for control of aquatic weeds in nonflowing water at 4 lb/100 gallons of water. do not use in water to be used for agricultural or domestic purposes.
	Floating and emersed weeds in southern waterways.	Liquid spray over surface.	2 to 8 lb/A	From 10 to 1,600 µg/l, 1 day after application. 1 to 70 µg/l, 5 weeks after treatment.	do	
Dichlobenil	Promising bottom treatments in canals without water.	Granules or wettable powder spray.	7 to 10 lb/A		Alfalfa-10, corn->10, soybeans-1.0, sugar beets-1.0 to 10.	Registered for control of submersed weeds in lakes, ponds, and drainage ditches where water not used for agricultural or domestic purposes.
Fenac	Same as dichlobenil	Same as dichlobenil.	10 to 20 lb/A	0.66 to 1.8 mg/l below treated area. 0.007 to 0.100 mg/l 2 hours later.	Alfalfa-1.0, corn-10, soybeans-0.1, sugar beets-0.1 to 10.	Same as dichlobenil.
Pichloram	For control of brush and weeds on watershed areas.	Liquid spray or granules.	1 to 3 lb/A	No data	Corn->10, field beans-0.1, sugar beets-<1.0.	Gives excellent control of Canada thistle and other bank weeds, but use near canals hazardous.

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[1] Data submitted by F. L. Timmons, Crops Protection Branch, Crops Research Division, ARS, USDA (unpublished).

[2] Data are for flood or furrow irrigation for all herbicides except when sprinkler irrigation is indicated for acrolein. Threshold of injury is lowest concentration that caused either temporary or permanent injury. Often this concentration did not cause final reduction in crop yield or quality.

[3] Estimates based upon very limited data and extensive observations.

Proposed changes in criteria

Current research is being directed toward relating the quality of water to specific crop and soil conditions and for different methods of application as well as amounts of water required. Much is known regarding salinity and its effects on soils and plants. In contrast, there is a paucity of knowledge of the effects of trace elements and heavy metals in irrigation water on growth and quality of plants. Little is known about the effects of organics having a biochemical oxygen demand (BOD) and other pollutants in irrigation water. Until more information is available, little can be done to improve on the guidelines and refinements of criteria now available.

Weed seeds in drainage water, particularly water to be reused for irrigation, should be classed as a pollutant and some criteria established for evaluation. Most other additions and changes in criteria will likely come gradually as the necessary research information becomes available.

Nature of Pollutants Involved

The quality of irrigation water and return flow is largely determined by the amount and nature of the dissolved and suspended materials they contain. In natural waters, the materials are largely dissolved inorganic salts leached from rocks and minerals of the soils through which the water passes. Use and reuse of water for irrigation and industry concentrates these salts and adds additional kinds and amounts of pollutants. Many insecticides, fungicides, bactericides, herbicides, nematocides, as well as plant hormones, detergents, salts of heavy metals, and many organic compounds, render water less fit for irrigation and other uses.

Salinity, hardness, and plant nutrients

The greater portion of the dissolved solids in most natural waters used for irrigation are sodium, potassium, calcium, and magnesium sulfates, chlorides, carbonates, and bicarbonates. There are wide variations in concentration and proportion of these salts, as indicated in Table 11 (32). The relative prevalence of the different kinds of salts in the streams of the United States is indicated in Figure 4.

Hardness is a significant quality characteristic of waters to be used for domestic or industrial purpose. Ordinarily hardness is

Table 11. Chemical analysis of important streams from which water is diverted for irrigation (32).

No.	Stream	Conductance ($K \times 10^5$ at 25° C)	Boron ppm	Percent sodium	pH	Silica ppm	Calcium epm	Magnesium epm	Sodium epm	Potassium epm	Total Cations epm	Carbonate epm	Bicarbonate epm	Sulfate epm	Chloride epm	Nitrate epm	Total Anions epm
1	Yakima [1]	11.7	0.02	23	7.6	19	0.56	0.35	0.28	0.04	1.23	0	1.00	0.07	0.15	tr	1.22
2	Sacramento [2]	15.0	0.05	18	7.9	25	0.63	0.51	0.26	0.04	1.44	0	1.22	0.13	0.12	tr	1.47
3	Columbia [3]	15.1	0.05	13	7.0	-	0.90	0.39	0.19	-	1.48	0	1.26	0.21	0.07	tr	1.54
4	Yellowstone [4]	19.1	0.06	29	7.5	-	0.89	0.59	0.61	0	2.09	0	1.18	0.52	0.10	0.03	1.83
5	North Platte [5]	28.0	0.03	22	7.5	15	1.61	0.57	0.63	0.07	2.88	0	1.59	1.12	0.09	0.03	2.83
6	Cache Creek [6]	50.8	1.78	32	-	-	1.31	2.40	1.77	-	5.48	0.40	3.37	0.61	1.05	tr	5.43
7	San Joaquin [7]	76.4	0.18	52	7.0	19	1.79	1.58	3.84	0.16	7.37	0	2.50	3.90	1.04	0.04	7.48
8	Arkansas [8]	93.3	0.08	25	8.2	22	5.06	2.66	2.63	0.21	10.56	0.05	2.70	7.39	0.47	tr	10.60
9	Rio Grande [9]	112	0.20	50	8.3	41	4.14	1.49	5.77	0.21	11.61	0.25	3.33	4.97	3.02	0.03	11.60
10	Colorado [10]	117	0.16	39	7.8	-	5.06	2.30	4.70	-	12.06	tr	2.52	7.16	2.30	0.03	12.01
11	Gila [11]	133	0.20	60	-	15	3.39	1.59	7.75	0.25	12.98	0.30	2.75	2.29	7.07	0.01	12.42
12	Pecos [12]	542	0.37	40	-	22	25.06	12.66	25.79	0.61	64.12	-	1.34	35.64	26.79	0	63.77

[1] Yakima River from main canal on Sunnyside Project; composite sample for August, 1943.

[2] Sacramento River at Tisdale, approximately 35 miles above Sacramento, July 13, 1945.

[3] Columbia River at Wenatchee, Washington, November 25, 1935.

[4] Yellowstone River from canal at Huntley, Montana, June 7, 1940.

[5] North Platte River from canal near Scotts Bluff, Nebraska, May 23, 1945.

[6] Cache Creek at Capay Dam, Yolo County, California; composite sample for August, 1941.

[7] San Joaquin River near Vernalis, California, August 10, 1933.

[8] Arkansas River at point of diversion of Rocky Ford High Line Canal, Pueblo County, Colorado, July 21, 1944.

[9] Rio Grande at El Paso, Texas; composite sample for August, 1945.

[10] Colorado River at Yuma, Arizona; composite sample for August 1-10, 1942.

[11] Gila River at Ashurst-Hayden Dam, Arizona, August 2, 1933.

[12] Pecos River near Orla, Texas, 19 miles downstream from Red Bluff Dam; composite sample for August 1-10, 1943. Analysis by U. S. Geological Survey (Water-Supply Paper 970, p. 70).

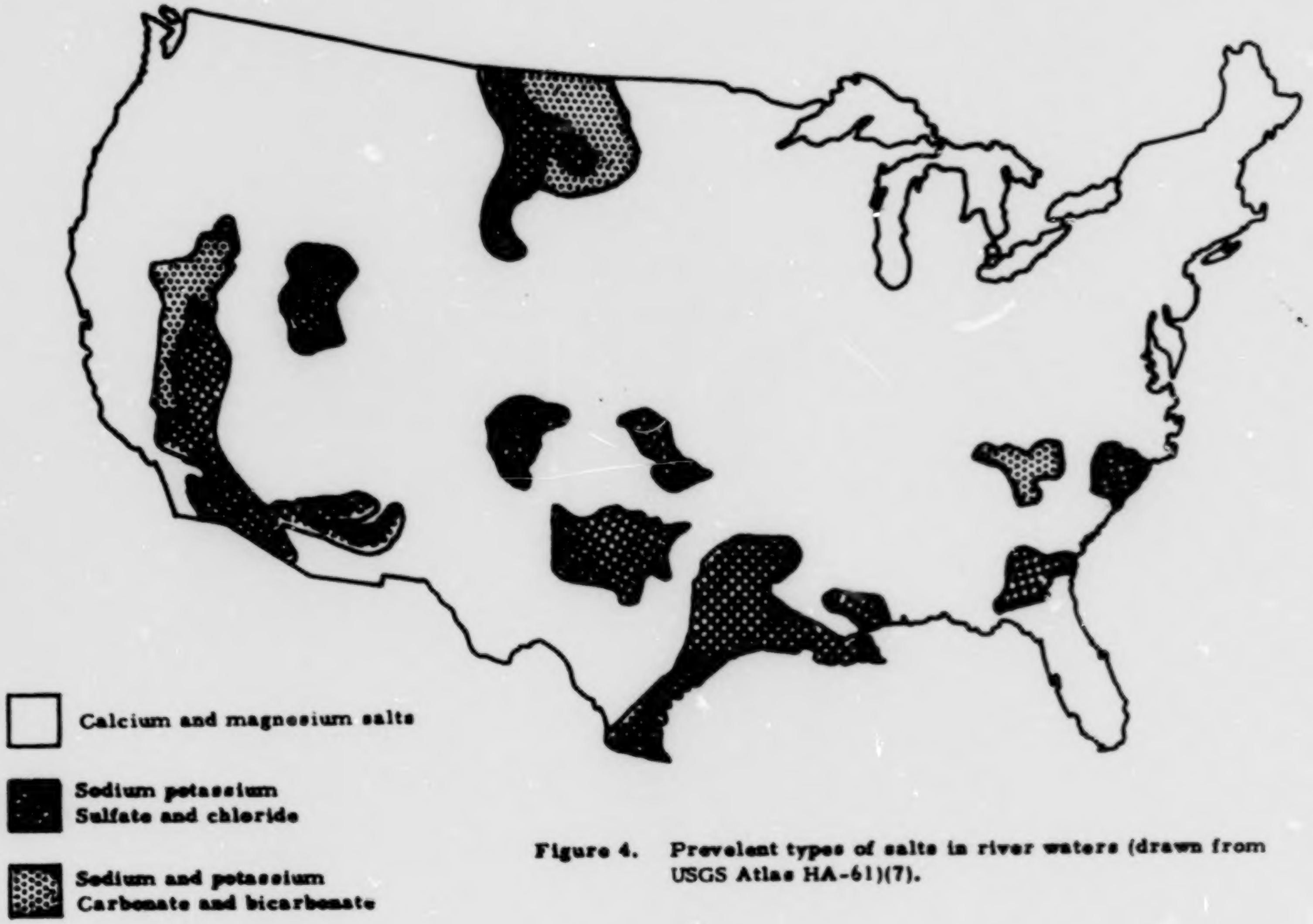
Calcium and magnesium salts
Sodium potassium
Sulfate and chloride
Sodium and potassium
Carbonate and bicarbonate

Figure 4. Prevelent types of salts in river waters (drawn from USGS Atlas HA-61)(7).

considered as the capacity to neutralize or precipitate soap. In irrigation waters, hardness is usually attributed to calcium and magnesium. Ions of iron, copper, barium, etc., are also responsible for hardness. It is expressed in terms of ppm calcium carbonate equivalent. Hardness is likely to be increased through the use of water for irrigation. Eldredge (33) indicates that usually a hardness of 75-150 ppm in water does not interfere with its use for most domestic purposes. Hardness of 150 ppm is marginal, and if above 200 ppm water usually should be softened. Hardness induced by calcium and magensium reduces the harmful effects of exchangeable sodium in soils.

Plant nutrients of major concern in irrigation waters are nitrogen in the form of nitrate and phosphorus as soluble phosphate. Usually the amounts of these nutrients in irrigation water will have little or no adverse effect on crops or soils. The harmful effects are reflected by the stimulation of growth of aquatic plants in lakes and in storage reservoirs and in conveyance canals and drains. Compounds of nitrogen and phosphorus have adverse effects when in water intended for uses other than for irrigation. An example is the toxic effect of nitrate consumed by infants. The quantity in most natural water is usually very low and an appreciable quantity generally indicates pollution. Evidence indicates that vigorous algae growth can be expected if water contains 0. 1 mg/l phosphorus and that levels must be below 0. 02 mg/l, if growth is to be completely inhibited (34).

Phytotoxic elements

Many substances appear in water at low concentrations and have specific adverse effects on plants. Boron is an example. It occurs in toxic concentrations in certain natural irrigation water and is introduced as a pollutant from many sources. Crop plants differ in their tolerance to boron, as indicated in Table 12 (35). When excess boron occurs in the water, tolerant crops may still be grown while sensitive crops could not. Boron does not leach from the soil as readily as do many other salts (36).

Many substances such as trace elements and/or heavy metals that are not in natural waters in toxic concentrations, are introduced as pollutants and may be harmful to plants and animals. Some crops are particularly sensitive to sodium and chloride ions and the adverse effect is due to specific toxicity rather than to increased osmotic pressure. A list of many of the known pollutants and their mode of actions is given in Table 13 (37).

Table 12. Relative tolerance of plants to boron in irrigation water (35).

Tolerant	Semitolerant	Sensitive
4.0 ppm of boron	2.0 ppm of boron	1.0 ppm of boron
Athel (Tamarix aphylla)	Sunflower (native) (Helianthus annuus)	Pecan (Carya pecan)
Asparagus (Asparagus officinalis)	Potato (Solanum tuberosum)	Walnut (black and Persian or English)(Juglans spp.)
Palm (Phoenix canariensis	Cotton (Acala and Pima) (Gossypium spp.)	Jerusalem artichoke (Helianthus tuberosus)
Date palm (Phoenix dactylifera)	Tomato (Lycopersicum esculentum	Navy bean (Phaseolus vulgaris)
Sugar beet (Beta vulgaris)	Sweetpea (Lathyrus odoratus)	American elm (Ulmus americana)
Mangel (Beta vulgaris)	Radish (Raphanus sativus)	Plum (Prunus domestica)
Garden beet (Beta vulgaris	Field pea (Pisum sativum)	Pear (Pyrus communis)
Alfalfa (Medicago sativa)	Ragged-robin rose (Rosa)	Apple (Pyrus malus)
Gladiolus (Gladiolus spp.)	Olive (Olea europaea)	Grape (Sultanina and Malaga) (Vitis vinifera)
Broadbean (Vicia faba)	Barley (Hordeum vulgare)	Kadota fig (Ficus carica)
Onion (Allium cepa)	Wheat (Triticum vulgare)	Persimmon (Diospyros spp.)
Turnip (Brassica rapa)	Corn (Zea mays)	Cherry (Prunus avium)
Cabbage (Brassica oleracea var. capitata)	Milo (Sorghum vulgare)	Peach (Prunus persica)
Lettus (Lactuca sativa)	Oat (Avena sativa)	Apricot (Prunus armeniaca)
Carrot (Daucus carota)	Zinnia (Zinnia elegans) Pumpkin (Cucurbita pepo) Bell pepper (Capsicum frutescens) Sweet potato (Ipomoea batatas) Lima bean (Phaseolus lunatus)	Thornless blackberry (Rubus spp.) Orange (Citrus sinensis) Avocado (Persea americana) Grapefruit (Citrus paradisi)
2.0 ppm of boron	1.0 ppm of boron	0.3 ppm of boron

Table 15. Potential pollutants with indication of degree of toxicity and mode of action (57).

Material	Degree of Toxicity[1]	Mode of Action[2]
Acids. Sulfuric, hydrochloric, nitric, acetic, and hydrogen sulfide. Beneficial to alkali soils. Excessive acidification of some soils might bring into solution toxic substances such as heavy metals	S to N	Os
Barium. Would be precipitated from most natural waters	S	Os
Beet-Sugar wastes	S to N	Os
Calcium. Desirable in reasonable concentrations	S to N	Os
Calcium Chloride. Tox to some stone fruits	S to N	Os
Chloride. Toxic to some plants	S	Os to Tox
Dissolved Solids. 90 percent of all irrigation waters contain less than 2,000 ppm	S to N	Os
Magnesium. Desirable in reasonable concentration	S to N	Os
Nitrate. A fertilizer and beneficial in moderate concentration, toxic to some plants at higher concentration	S to N	Os
Phosphate. A fertilizer and beneficial in reasonable concentration. Precipitated from most irrigation waters	N	Os
Potassium. A fertilizer and beneficial in small amounts	S to N	Os
Sulfate	S to N	Os
Alkalinity. May be beneficial in small amounts for acid soils	M	Soil
Ammonium Salts. Soil impairment not as pronounced as with sodium salts. Beneficial as a fertilizer in reasonable quantity	S	Soil
Bicarbonate. In addition to soil impairment it may cause a "bicarbonate-induced chlorosis" on some plants	S	Soil
Fluoride. May precipitate as CaF_2 causing calcium deficiency or soil impairment	M	Soil
Sodium Salts. Soil impairment is the principal hazard, although sodium is moderately toxic to some plants	S	Soil
Sodium Carbonate	S	Soil
Aluminum. Less toxic in alkali soil or in alkaline solution	Ex	Tox
Arsenic. Less toxic in alkaline solution. Can accumulate in soil to toxic levels	Ex	Tox
Beryllium. Less toxic in alkali soil or in alkaline solution	M	Tox
Boron Compounds	Ex	Tox
Cadmium. Less toxic in alkali soil or in alkaline solution	S	Tox
Chemical Warfare Agents	Ex	Tox
Chlorine. No toxic effect at concentration below 50 ppm	S	Tox
Chromium. Less toxic in alkali soil or in alkaline solution	M	Tox
Cobalt. Less toxic in alkali soil or in alkaline solution	Ex	Tox
Copper. Less toxic in alkali soil or in alkaline solution	Ex	Tox
Gallium	Ex	Tox
Halogenated Hydrocarbons. Might impart objectional flavors or odors; weed killers, DDT, Lindane, BHC, Chlordane, Gammexane, Benoclor	M to S	Tox
Indium	Ex	Tox
Iron. Less toxic in alkali soil or in alkaline solution	S	Tox
Lead. Less toxic in alkali soil or in alkaline solution	S	Tox
Lithium	Ex	Tox
Manganese. Less toxic in alkali soil or in alkaline solution	Ex	Tox
Molybdenum. Less toxic in acid soil or in acid solution. Accumulates in plant tissue; forage toxic to animals	M	Tox
Nickel. Less toxic in alkali soil or in alkaline solution	Ex	Tox
Nitrite	M	Tox
Oil, Petroleum	S	Tox
Palladium. Toxic "at comparatively low concentrations"	. . .	Tox
Rubidium	S to N	Tox
Selenium. Accumulates in plant tissue; forage toxic to animals	M	Tox
Sodium Carbonate. Also impairs soil	M	Tox
Sodium Chloride. Also impairs soil	S to N	Os to Tox
Strontium	S	Tox
Tellurium. "Low concentration of K_2TeO_3 in culture solution reduced growth"	. . .	Tox
Thorium	S	Tox
Tin. Less toxic in alkali soil or in alkaline solution	M	Tox
Titanium	S to N	Tox
Zinc	M	Tox

[1] Ex, extreme toxicity; M, moderate; S, slight; N, nontoxic.

[2] Mode of action; Os, osmotic; S, soil impairment; Tox, phytotoxic.

Pesticides

Bactericides, fungicides, insecticides, nematocides, rodenticides, and herbicides as a group of pesticides include both organic and inorganic compounds that can pollute soils or water. These can be classed in four broad groups:

(a) Halogenated hydrocarbons are compounds of carbon hydrogen and chlorine, or bromine used as insecticides or herbicides. They are used in the largest quantities and are likely to be found most in the soil. Some of the common named products are: endrin, toxaphene, dieldrin, aldrin, DDT, methoxychlor, heptachlor, lindane, chlordane, and BHC.

(b) Organophosphates are compounds of carbon, hydrogen, oxygen, and phosphorus. Most are readily decomposed in the soil or water and serve as a source of phosphorus pollution. In common use are: EPN, para-oxon, TEPP, parathion, chlorothion, systox, methyl parathion, malathion, dipterex, and OMPA.

(c) Other organics include such compounds as carbamates, phenoxys, thocynates, substituted ureas, triazines, organic mercurials, and nicotine.

(d) Inorganics include such compounds as lead and calcium arsenate and copper sulfate.

Sediments and turbidity

Sediments are as variable as the soils from which they are derived. Suspended solids in water can affect the use of water in many ways. In surface irrigation, the solids can interfere with flow in conveyance systems and structures. Deposits can reduce the capacity of reservoirs and distribution systems. Suspended minerals may cause undue wear on sprinkler nozzles and pumps, clog screens, and adversely affect water for most domestic and industrial uses. Sediments may be relatively large mineral particles that tend to settle out of suspension or fine colloids that remain in suspension. Algae growth can cause turbidity in water. Heavy metals and many pesticides are absorbed by organic and mineral soil particles, transported while adsorbed on soil particles, and contaminate surface waters as a result of erosion (38).

Organic matter, taste, odor, and color

Taste, odor, and color are of little concern in the use of water for irrigation. The prime objections are raised by other users and they vary with the nature of the compounds responsible for the objectionable characteristics. Biodegradable organic matter is of concern to most water users. Soil aeration and availability of oxygen is usually no problem in well structured soils. Where drainage is poor, the oxygen supply may be limited. Waters containing organics with high BOD aggravate soil aeration and availability of oxygen in the soil. Organics with a wide carbon-nitrogen ratio could also induce a deficiency of nitrogen in a growing crop. Decomposing organic matter causes objectionable taste, odor, and color. Pesticides in the water can kill fish and plants, resulting in disagreeable odors and tastes. Some pesticides impart disagreeable odors and tastes directly due to the materials themselves.

Thermal pollution by irrigation

Relatively nothing is known concerning the temperature changes that might take place in return flow waters between their point of diversion and subsequent return to the supply system. Irrigation is applied under a wide range of temperature conditions involving water temperature, soil temperature, and air temperature. Late fall and winter irrigations might have a general cooling effect on the total return flow, depending upon the lag time between the diversion and return. On the other hand, summer irrigations on hot soils might produce warmer return flows. The cooling effect produced by the "latent heat of vaporization" for all water transpired or evaporated may be significant under certain conditions. Depending upon the initial temperature (soil, water, and air), the thermal pollution could be either positive or negative. Relatively hot waters produced in cooling requirements of industry would probably be cooled substantially if used for irrigation. The general thermal pollution effect of irrigation on the return flow portion is believed to be of a moderating type with the irrigation process being either a positive or negative contributor of heat, depending upon initial conditions.

A substantial increase in the temperature that would adversely affect the water for future use can be considered as thermal pollution. The major effect of thermal pollution seems to be on cooling water and on aquatic life in streams and reservoirs.

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SOURCES AND DETECTION OF POLLUTANTS

Sources of Pollutants in Irrigation Water and Return Flow

Pollutants in irrigation or drainage waters come from many sources before, during, and after irrigation. They come from animals, soils, both irrigated and non-irrigated, fertilizers and amendments, pesticides, as well as from industrial and municipal wastes. Some pollution is natural, such as from mineral springs, lightning, fixed nitrogen, etc. An example of the diverse contributions to salinity increase in the Colorado River is given in Table 14.

Soil derived

As irrigation and rain water percolate through the soil mantle, the soluble mineral constituents of weathered rocks are dissolved and move with the water. Some salts may have been transported to the soil and accumulated where the water was consumed, or they may have been released from weathering of rocks and minerals. Soils containing considerable gypsum will contribute soluble calcium sulfate for an extended period as indicated by Doneen (36), except where saline soil is being leached. Most of the salt in drainage water from irrigated fields was at one time or another in the irrigation water. Where drainage is established and salty soils are leached, the salt load in the drainage water will be much greater than in the irrigation water, and there will be a favorable salt balance for the area and a greater than normal concentration in the return flow. This was shown by Bower, Spencer, and Weeks (39) in their salt balance study in the Coachella Valley, California, Table 15. As the proportion of the land with tile drainage increased so did the salt removal until there was a favorable salt balance established. The data undoubtedly indicate that some saline soils were being reclaimed after drainage was established.

The data in Table 16 (39) shows the accompanying changes in composition of Colorado River water as a result of use in the Coachella Valley. Most striking is the increase in sodium and the decrease in calcium and magnesium. The nitrate ion is completely soluble in the soil solution and generally moves with the soil solution. Nitrates are formed in soils when organic matter is nitrified by soil

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Table 14. Incremental salt concentration attributable to specific sources, Colorado River at Hoover Dam (40) (1942-1961 period of record adjusted to 1960 condition)[1].

Sources	Total dissolved solids mg/l
Natural Sources	
Diffuse Sources	274
Point Sources (mineral springs, wells, etc.)	69
Irrigation	
Consumption	88
Leaching	165
Municipal and Industrial Sources	10
Water Exports	22
Evaporation and Phreatophytes	97
TOTAL	725

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[1] Based on data from: USGS Professional Paper 441, Water Resources of the Upper Colorado River Basin, 1965; USDI, Progress Report No. 3, Quality of Water, Colorado River Basin, January 1967; FWPCA records on open files.

Table 15. Acres of irrigated and tiled land, and inputs and outputs of water and salt for irrigated land by years, 1957-1965, Coachella Valley, California (39).

Year	Irrigated land	Irrigated land with tile drainage acres	Inputs to irrigated land, (Colorado River plus wells)			Outputs from irrigated land		
			Water ac-ft	Salt		Water ac-ft	Salt	
				tons/ac-ft	tons		tons/ac-ft	tons
1957	52,329	10,835	299,590	1.234	369,655	32,578	3.065	99,847
1958	53,592	14,585	348,590	.968	337,340	46,467	3.369	156,542
1959	55,527	19,115	358,641	.972	348,543	47,188	3.530	166,553
1960	54,333	22,285	368,926	.987	364,265	61,327	3.721	228,215
1961	53,990	24,857	366,315	1.066	390,522	75,597	3.666	277,169
1962	53,443	27,071	389,877	1.122	437,313	101,169	3.425	346,506
1963	57,773	28,984	370,014	1.058	391,459	110,627	3.640	402,685
1964	60,053	30,686	359,989	1.128	406,110	113,104	3.660	413,978
1965	59,890	32,080	341,165	1.193	406,992	124,128	3.423	424,837

Table 16. Comparison of the composition of Colorado River water with that of drainage water (39).

Date	Equivalent percentage of total cations				Equivalent percentage of total anions			
	Ca	Mg	Na	K	CO_3+ HCO_3	SO_4	Cl	NO_3
Colorado River (Coachella Branch of All-American Canal)								
Aug. 1963	37.22	20.28	41.41	1.09	22.04	53.83	23.97	.17
Mar. 1964	38.49	20.73	39.23	1.55	22.20	50.77	26.80	.23
Aug. 1964	35.22	19.25	44.33	1.19	18.10	53.70	27.90	.15
Feb. 1965	41.06	13.20	43.99	1.76	20.57	50.55	28.66	.22
Aug. 1965	34.50	19.34	45.18	.98	17.19	54.61	28.20	.[illegible]
Apr., 1966	36.46	18.91	43.42	1.22	19.55	50.91	29.33	.21
Aug. 1966	33.81	19.07	46.09	1.03	18.94	52.57	28.28	.20
Ave.	36.68	18.68	43.38	1.26	19.80	52.42	27.45	.20
Coachella Valley Main Drain								
Aug. 1963	23.24	10.54	65.35	.87	15.05	52.82	32.13	-
Mar. 1964	25.95	6.23	66.55	1.27	14.89	44.29	40.15	.67
Aug. 1964	23.06	9.84	66.00	1.10	14.98	51.09	33.94	-
Feb. 1965	29.03	4.38	65.46	1.12	15.91	46.53	36.84	.73
Aug. 1965	24.53	10.64	63.97	.86	15.14	50.70	34.16	-
Apr. 1966	28.08	7.49	63.06	1.37	15.26	40.24	43.60	.90
Aug. 1966	24.10	10.42	64.53	.95	13.79	53.75	32.46	-
Ave.	25.43	8.51	64.99	1.08	15.00	48.49	36.18	.77
Average for Main Drain Minus Average for Colorado River								
	-11.25	-10.17	21.61	-.18	-4.80	-3.93	8.73	.57

organisms. Nitrates move with water and other soluble salts into the drainage system, unless the nitrate ions are used by the growing crop, by micro-organisms, or undergo dentrification in a reducing atmosphere. The possibilities for some nitrate to get in the drainage or groundwater are so numerous that it is difficult to generalize on the amounts contributed by the soil as a result of irrigation.

The soluble phosphorus content of the soil solution of most soils is low. Biggar and Corey (41) report that the soluble phosphorus in the soil solution of surface soils seldom exceeds 0.2 mg/l with a common range of 0.01 to 0.1, with displaced soil solutions of 0.03 for surface soils and subsoil soil solutions frequently less than 0.01 mg/l. Except for very coarse soils, most have a high fixing capacity for phosphate. If irrigation water contains appreciable amounts of phosphorus, 1 mg/l or more, the concentration in the drain would likely be less than in the original water as a result of the "fixation" of phosphorus by the soil. If the phosphate content of the irrigation water is nil, then there may be an increase in the phosphate content of the drainage water as a result of release of phosphorus from the soil particles, from organic matter, and from the phosphorus in the soil solution. Whether phosphorus is added to or removed from the water is dependent on the concentration of phosphorus in the irrigation water and on the nature of the soil through which the water percolates. Phosphates are carried into water with sediments and dust from the land and also in the form of organic materials. Oxidation of the organics in the water can account for some of the soluble phosphate in the return flow. Some phosphorus can also come from the soil materials in the bottom and banks of ditches and drains. Sorption and release of phosphorus have a vital influence in increasing or decreasing the amount of phosphorus in solution.

Climate has a major effect on the kind of soils produced and on the kind and amount of salts in the return flow when the soils are irrigated. In the weathering process of rocks and minerals, the highly soluble salts of sodium and potassium are first to be released. These are leached from the profile and carried to the ocean, moved by water to another position, or accumulate in the profile if precipitation is low. In humid climates weathering and leaching progress much faster than in dry and/or cold climates.

When soils in humid areas are irrigated, climate also influences the composition of the return flow. The amount of irrigation water required is small compared to that required in warm and dry areas, and there is a low concentration of salts in the drainage water. The proportion of sodium and potassium salts in the drainage water is small in comparison to iron and aluminum. In a warm-dry climate the soils are less mature and contain considerably more salts of sodium, potassium, calcium, and magnesium. When irrigated, the natural waters likely contain more salt than in humid areas, and more irrigation water is required for crop production.

Climate, then, is a major factor responsible for the salinity and sodium problems found in the arid irrigated areas of the West. Climate can have many indirect effects on pollution. The amount and intensity of precipitation can also influence the amount of erosion and the accompanying sediment load of the return flow. Many of the pesticides are moved with the eroded mineral and organic soil particles.

Van Denburgh and Feth (42) estimated the annual solute erosion in 11 important river basins, Table 17. The wide range in tonnage was attributed to a complex of causes, among which were differences in geology, climatic environment, and the activities of man. Rates of solute removal were highest in areas of abundant precipitation and runoff, in contrast to rates of sediment removal, which are characteristically highest in basins subject to 10-15 inches effective annual precipitation.

Concentration by evapotranspiration

Consumptive use of water by evaporation and/or transpiration concentrates the pollutants in the water. Unless the pollutants precipitate, are adsorbed or decompose, the concentration will be in proportion to the amount consumed. When water is used to irrigate soils, most salts in the water will be concentrated in the drainage water. Many other changes in the water may occur as a result of passing the water through the soil, as previously explained under "Irrigation Practice."

Fertilizers and amendments

To understand the problem of pollution of drainage water from fertilizers, it is necessary to understand the factors which affect the forms and solubilities of the plant nutrients and the manner in which these are transported into the return flow. The nutrients of major concern as pollutants are nitrate-nitrogen and phosphorus. Nitrate in the drainage water can originate from rain, dust, soil, organic matter, manures, an accumulation in the soils prior to irrigation, fixation by micro-organisms, fertilizers, and from the wastes in urban and industrial runoff. It is removed from the soils by crops, by dentrification, and by drainage water. It is, therefore, difficult to determine the source of nitrate in drainage water.

Table 17. Rates of runoff and solute erosion for the period 1952-1957 (except as noted)[1] (42).

River and Station	Drainage basin area mi^2	Average yearly runoff, acre-ft	Average solute load removed			Weighted solute-erosion rate, tons mi^{-2} yr^{-1}
			Concentration, ppm	Tons per year	Tons mi^{-2} yr^{-1}	
Columbia near Rufus, Oregon[2]	177,000	66,600,000	132	12,000,000	68	
Willamette at Salem, Oregon	7,300	19,600,000	50	1,340,000	180	170
Rogue at Grants Pass, Oregon[3]	2,420	3,180,000	77	335,000	140	
Sacramento at Knights Landing, Calif.	15,000	7,860,000	168	1,320,000	88	71
San Joaquin near Vernalis, Calif.	14,000	3,240,000	167	738,000	53	
Colorado near Grand Canyon, Arizona	138,000	11,300,000	615	9,460,000	68	
Gila below Gillespie Dam, Arizona	49,600	46,800	327	208,000	4.2	12
Rio Grande at El Paso, Texas[4]	36,600	523,000	896	638,000	17	
Pecos near Red Bluff, New Mexico	19,500	73,600	4,630	464,000	24	
N. Platte below Guernsey Res., Wyo.	16,200	949,000	406	524,000	32	59
Yellowstone near Sidney, Montana	69,400	8,000,000	419	4,560,000	66	
Entire 11-Basin Area	545,000	121,000,000	192	31,600,000	58	

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[1] Data from U. S. Geological Survey (1956-1961), except as noted.

[2] Data do not include contributions of Columbia River basin upstream from station at international boundary.

[3] Data for 1953-1957 only.

[4] Data for 1931-1936; from National Resources Committee (1938).

The presence of plant nutrients in surface water is often attributed to a seemingly large tonnage of fertilizers applied to the land for maximum crop production. Yet, the amount of fertilizers applied to the soils of the United States is low compared to the amount used in the Netherlands, as shown in Table 18 (34).

Table 18. Plant nutrients applied in 1965 (34).

	Average pounds per acre	
Nutrient	United States	Netherlands
Nitrogen	22	244
P_2O_5	17	93
K_2O	13	116

On much of the land the amount of fertilizer applied is less than that used by the crop. A low average application, however, does not exclude the possibility of excessive amounts being used on some acreage. On some high value crops, such as celery, the common practice is to make heavy applications of fertilizers, particularly nitrogen, coupled with frequent irrigations. In such cases it is likely that considerable nitrate may be leached with the excess water and appear in the drainage system.

Doneen (36) concluded from a careful study in the San Joaquin Valley of California that in one field receiving heavy application of fertilizer a large portion of the nitrate in the drainage water was from the fertilizer. In two other fields recently drained, he could not come to the same conclusion because nitrates had been accumulating in the subsoil and groundwater for a long time. It is estimated that from combined sources the nitrate-nitrogen content of the water in the San Luis drain will be 20 mg/l (43).

Phosphate fertilizers can increase the phosphorus content of drainage water in several ways: percolating water passing through a heavily fertilized sandy soil low in fixing capacity will carry soluble phosphorus into the drains. Fertilizers applied to the surface of soils tend to stay near the surface and saturate the "fixing"site. When the fertile surface particles are eroded by wind or surface runoff, the phosphorus is carried with the sediments into the drainage system. Here the phosphate equilibrates with the phosphorus in the drainage water and may increase the concentration in solution unless the content of the water is at or above the equilibrium concentration.

Biggar and Corey (41) speculate that runoff water in contact with fertile surface soils can pick up soluble phosphorus as it moves over the surface of the land and that the concentration in the runoff water might range up to a few tenths of a mg/l.

Phosphate fertilizer can also have a less direct effect: it can stimulate plant growth, and then parts of the plant, such as dried leaves, are carried by wind or water into the drainage water where the plant material is mineralized by micro-organisms, with the resulting accumulation of soluble inorganic phosphorus in the water.

Johnston et al (44) studied N and P loss in tile drainage effluents from a number of tile drainage systems in irrigated areas in the San Joaquin Valley of California. A number of cropping practices, with crops (cotton, alfalfa, rice), fertilizers and irrigation water applications as variables were involved in the study. Initial tile effluent analysis in a previously unirrigated noncropped area showed an N concentration of 1 mg/l. Another system that had been cropped to alfalfa and had a low discharge over the period of a year yielded a range of N between 2.0 and 14.3 mg/l. On systems where high rates of N fertilizer were applied, the concentrations ranged up to 62.4 mg/l. In the systems reported, the range of concentrations of nitrates varied from 1.8 to 62.4 mg/l, with a weighted average of 25.1. The loss of nitrogen in the drainage flow was significant, but the percentage loss of phosphorus was not.

Both nitrogen and phosphorus can be carried directly into the surface drains with the tail water from fields where the fertilizer is being applied in the irrigation water. Other sources of nutrient pollution are the animal wastes in runoff from pastures and feedlots which may be commingled with the irrigation return flow.

Pesticides

Pesticides are recognized potential pollutants in water. As with nutrients the origin is not restricted to agricultural usage. Pesticides are used in cities, industrial areas, and forests as well as on farms. They can enter the water by direct application from drift during application or be washed in from adjacent lands adsorbed to eroded sediments. Pesticides can thus also pollute the waters of irrigation return flow. There is nothing unique about pesticide pollution and irrigation except perhaps where pesticides are used to control weeds and insects along irrigation canals and open drains.

Many of the pesticides used are sorbed chemically and physically by the soil particles. Those thus sorbed are not likely to enter subsurface drainage waters. LeGrand (45) reporting on movement of pesticides in soils suggests that it is likely that most pesticides in streams result from overland flow. Nicholson (46), in discussing pesticide pollution control, states:

> The two principal sources of water pollution by pesticides today are runoff from the land and discharges of industrial waste, either from industries that manufacture or formulate pesticides or from those that use these compounds in their manufacturing processes. Less important causes of pollution are (i) activities designed to control undesirable aquatic life, (ii) careless use of pesticides, and (iii) occasional accidents in transportation.

Johnston et al (47) analyzed drainage effluent from systems located on irrigated land in the San Joaquin Valley of California. On experimental areas the insecticides DDT, Parathion, and Lindane had been added. Only relatively small quantities of chlorinated hydrocarbon residues were found in the tile drainage effluent, but higher concentrations were found in the effluent from open drains where both surface and subsurface drainage waters were collected. Traces of residue were found in the irrigation water applied to tile-drained farms. When the concentration factor was considered, i. e., depth of irrigation water applied / depth of drainage water removed, on a unit basis, the total quantity of insecticide residue in the tile drainage effluent did not exceed, and was generally less than, the total quantity of residue applied in the irrigation water. Tail water, or surface runoff, contained from seven to 12 times more residue than the applied water when DDT was used on the land, and as much as 85 times more residue than the irrigation water when Lindane was applied to the land. Relatively large concentrations of residue were found also in the surface soil of the area studied.

As a generalization, it appears that the chlorinated hydrocarbons such as DDT persist in soils (48, 49) and do not move in appreciable concentrations through the soils and into the drainage effluent as groundwater. Movement is primarily with suspended sediment, either organic or inorganic materials in streams and open drain flow. The thiophosphates such as Parathion decompose rapidly and do not persist in soils or water.

Pesticides can be transported in the air while applications are being made and be deposited in water remote from the area of application (50). Wind can remove surface soil to which is adsorbed pesticides and this can be deposited by rain or the settling dust.

Faulkner (51) found large numbers of nematodes, including plant parasites, in irrigation and drainage waters. There is no indication yet as to the nature and magnitude of any pollution problems that might accompany the treatment of water for the control of nematodes.

Indirectly, pesticides may add other pollutants to soil and water. The organic phosphorus insecticides and miticides readily decompose in soil and release soluble phosphorus. Other organic pesticides are composed of compounds containing mercury, zinc, manganese, copper, chromium, cadmium, and tin. When the organic compounds are decomposed, the metal ions are released.

Municipal and industrial supplies

The occurence of municipal and industrial waste waters in water supplies used by irrigated agriculture may be the result of incidental discharges into a common receiving water subsequently used for irrigation or from direct, intentional application of such waste waters as a prime source of supply. In either case, the nature and concentration of any constituent that may be considered as a potential pollutant will depend upon the specific characteristics and origin of the waste water; i. e., whether (a) of purely domestic origin, (b) a combination of domestic and industrial origin, or (c) essentially an industrial discharge. In addition, the characteristics of the waste water may be ameliorated by the degree of treatment and/or dilution afforded the effluent prior to use.

Nature and extent of practice of using waste waters.

The practice of using municipal waste waters for irrigation purposes in the United States evolved during the latter part of the nineteenth century, following the advent of the water-carriage system of domestic waste disposal. While historically this practice probably originated from considerations of the fertilizer value of sewage, the primary impetus for using municipal sewage for irrigation in this country stemmed from the need to augment the limited water supplies and inadequate rainfall associated with the arid and semi-arid areas of the West.

Table 19 indicates that in terms of overall quantity needs for irrigation, the contribution possible from reuse of municipal supplies would be extremely modest even if it were all available for this purpose. On the other hand, the magnitude of industrial use of water and the relatively small consumptive losses from such use might make this appear promising as a source of supply. Unfortunately, the relationship between location of major water-using industries and irrigated agricultural areas, as shown in Table 20 and Figure 5, limits this possibility. An additional difficulty in using municipal and industrial

Table 19. United States: Estimated water use, 1900-1975 (Billions of gallons; daily average)(61).

Year	Irrigation	Public Water Supplies	Domestic	Self-Supplied	Steam-Electric Power	Total
				Industrial and Miscellaneous		
1900	20.2	3.0	2.0	10.0	5.0	40.2
1910	39.0	4.7	2.2	14.0	6.5	66.4
1920	55.9	6.0	2.4	18.0	10.0	92.3
1930	60.2	8.0	2.9	21.0	18.4	110.5
1940	71.0	10.1	3.1	29.0	22.2	135.4
1944	80.6	12.0	3.2	56.0	35.9	187.7
1945	83.1	12.0	3.2	48.0	28.8	175.1
1946	86.4	12.0	3.5	39.0	26.9	167.8
1950	100.0	14.1	4.6	46.0	38.4	203.1
1955	119.8	17.0	5.4	60.0	59.8	262.0
1960	135.0	22.0	6.0	71.9	77.6	312.5
1965	148.1	25.0	6.5	87.7	92.2	359.5
1970	159.0	27.8	6.9	103.0	107.8	404.5
1975	169.7	29.8	7.2	115.4	131.0	453.1

Table 20. Regional incidence of industrial waste discharge, by major industrial sectors, 1964 (40).

Industry	Percent of Discharge of Industry's Wastewater													
	Regionally Assignable Discharge	North-east	South-east	Great Lakes	Ohio	Ten-nessee	Upper Missis-sippi	Lower Missis-sippi	Mis-souri	Arkansas White-Red	Western Gulf	Colorado and Great	Pacific North-west [1]	Cal-fornia [2]
Meat products	90.6	5.0	7.0	4.0	6.0	-	32.3	1.0	23.2	4.0	2.0	-	5.1	1.0
Dairy products	64.0	10.3	3.4	22.4	3.4	-	7.2	-	5.2	-	-	-	5.2	6.9
Canned & frozen foods	68.8	2.4	18.4	8.0	-	-	3.4	-	-	-	-	-	14.9	20.7
Sugar refining	56.7	6.3	-	-	-	-	-	36.4	10.4	-	-	-	-	3.6
All other food products	95.1	21.0	4.3	15.5	7.1	.9	20.1	4.3	4.9	1.0	1.5	1.5	5.0	7.1
Textile mill products	98.4	31.1	55.6	1.5	.6	8.1	-	1.5	-	-	-	-	-	-
Paper & allied products	98.3	23.5	26.4	12.4	2.6	3.4	5.6	1.6	.1	3.4	1.4	-	16.7	1.2
Chemical & allied products	100.0	12.8	5.0	13.0	19.7	6.7	1.6	5.4	.4	1.3	32.0	.1	1.2	.8
Petroleum & coal	97.6	26.8	.4	19.7	1.8	-	.8	9.1	1.6	1.1	25.5	.2	.2	10.5
Rubber & plastics, n.e.c.	76.8	22.6	3.9	36.8	5.8	-	2.6	2.6	1.9	-	-	-	-	.6
Primary metals	87.8	7.4	1.0	38.4	33.4	.5	2.3	-	.3	-	3.2	.2	.9	.2
Machinery	100.0	49.6	.7	16.8	8.1	-	22.8	-	-	-	.7	.7	-	.7
Electrical machinery	99.0	35.2	3.3	19.8	28.6	1.1	6.6	-	1.1	1.1	-	-	-	2.2
Transportation equipment	98.2	31.2	1.7	46.8	5.9	-	2.1	-	-	.8	-	-	1.7	8.0
All other (plus unassignable)	-	95.7	4.0	18.1	8.7	8.1	11.9	35.6	1.7	6.6	4.3	7.2	18.8	8.1
Total industrial discharge		19.9	6.9	23.4	18.2	2.4	3.5	3.7	1.2	1.4	12.0	.3	4.1	2.7

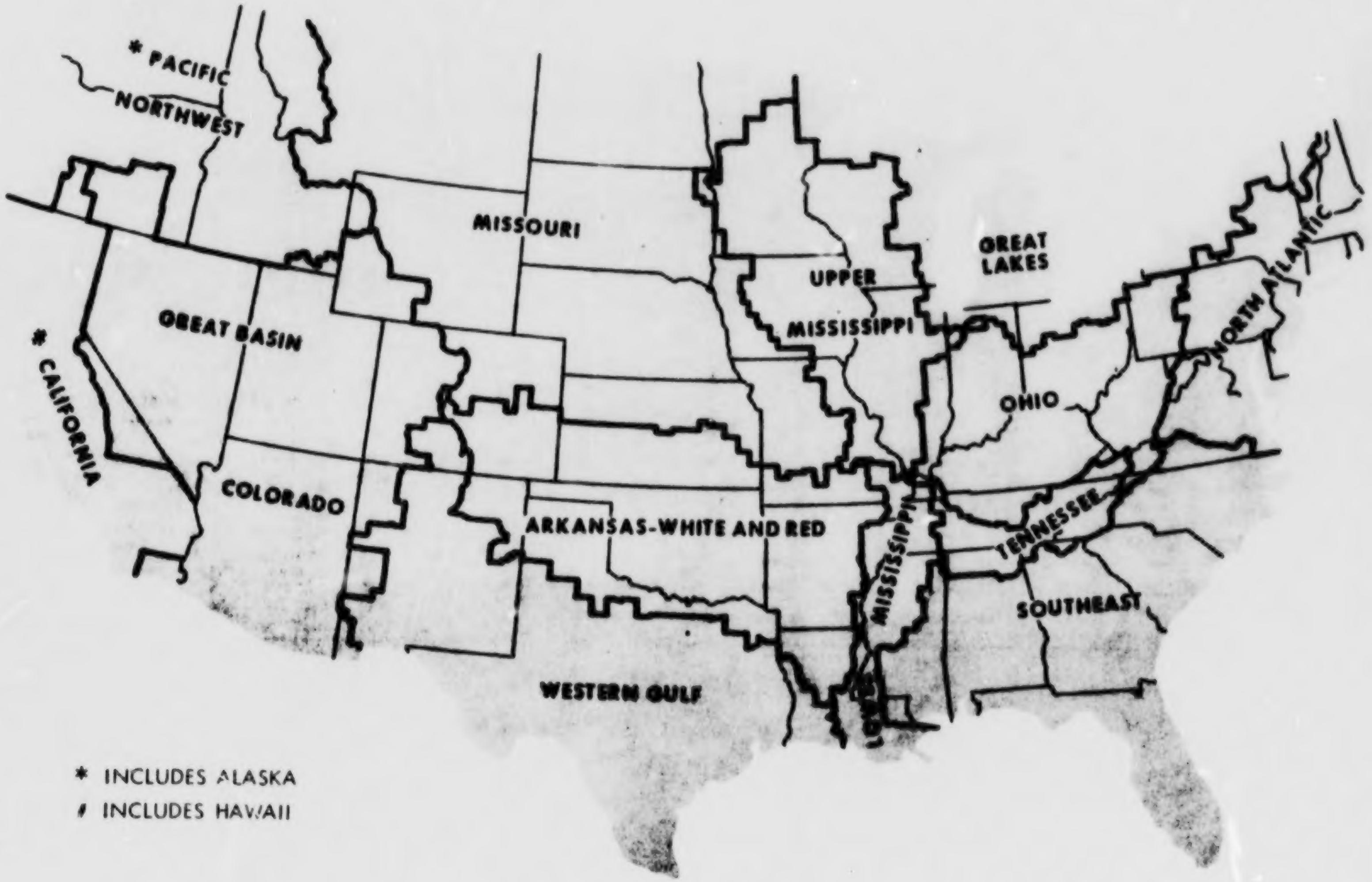
* PACIFIC NORTHWEST
MISSOURI
UPPER MISSISSIPPI
GREAT LAKES
NORTH ATLANTIC
GREAT BASIN
# CALIFORNIA
OHIO
COLORADO
ARKANSAS-WHITE AND RED
MISSISSIPPI
TENNESSEE
SOUTHEAST
WESTERN GULF
LOWER
* INCLUDES ALASKA
# INCLUDES HAWAII

Figure 5. Major drainage regions, industrial definitions (40).

effluents for irrigation is the poor correlation between crop needs and waste water flows. In some instances, however, groundwater recharge and storage of these effluents for subsequent use is feasible.

Thomas and Law (52) recently reported that of about 1,300 soil systems receiving surface applications of waste waters in the United States in 1964, about two-thirds of these systems were being used specifically for waste water treatment, while in the remaining one-third of the systems, irrigation of crops was the primary objective.

Use of municipal and industrial waste waters for irrigation supply is currently of minor importance in the total needs of irrigated agriculture, although these sources may be significant in certain localities. Dual purpose use of effluents for crop irrigation, as well as economical and efficient method of treatment and disposal, appears to be emerging as an attractive concept for some municipalities and industries, and may become a significant factor in the extent of this reuse practice.

Before examining the characteristics of municipal and industrial waste waters, it is appropriate to review the potential pollutants in irrigation waters summarized by Wilcox (37) in Table 13 as a basis for evaluation of the suitability of these waste waters as a source of supply.

Characteristics of municipal waste waters. (a) Biological considerations. In the United States the practice of using raw sewage for irrigation was essentially abandoned in the early part of this century, and by the 1930's a minimum of primary treatment was required (53). Early requirements for the use of municipal sewage effluents were primarily concerned with the health hazards involved and, in general, limited the use of such water to crops other than those used for human consumption.

An example of a recent coliform requirement for water used for various irrigation purposes, established by the California State Department of Public Health in 1967, is shown in Figure 6 (54). Compliance with this requirement is accomplished by primary and secondary treatment, disinfection with chlorine, minimizing public contact with the reclaimed water, irrigation during non-use periods, as well as other measures.

(b) Chemical quality. The composite chemical quality of raw municipal waste water is only slightly affected by conventional primary and secondary treatment and thus is basically the sum of the constituents comprising the chemical quality of the original water supply and the constituents added through municipal use. This "municipal use

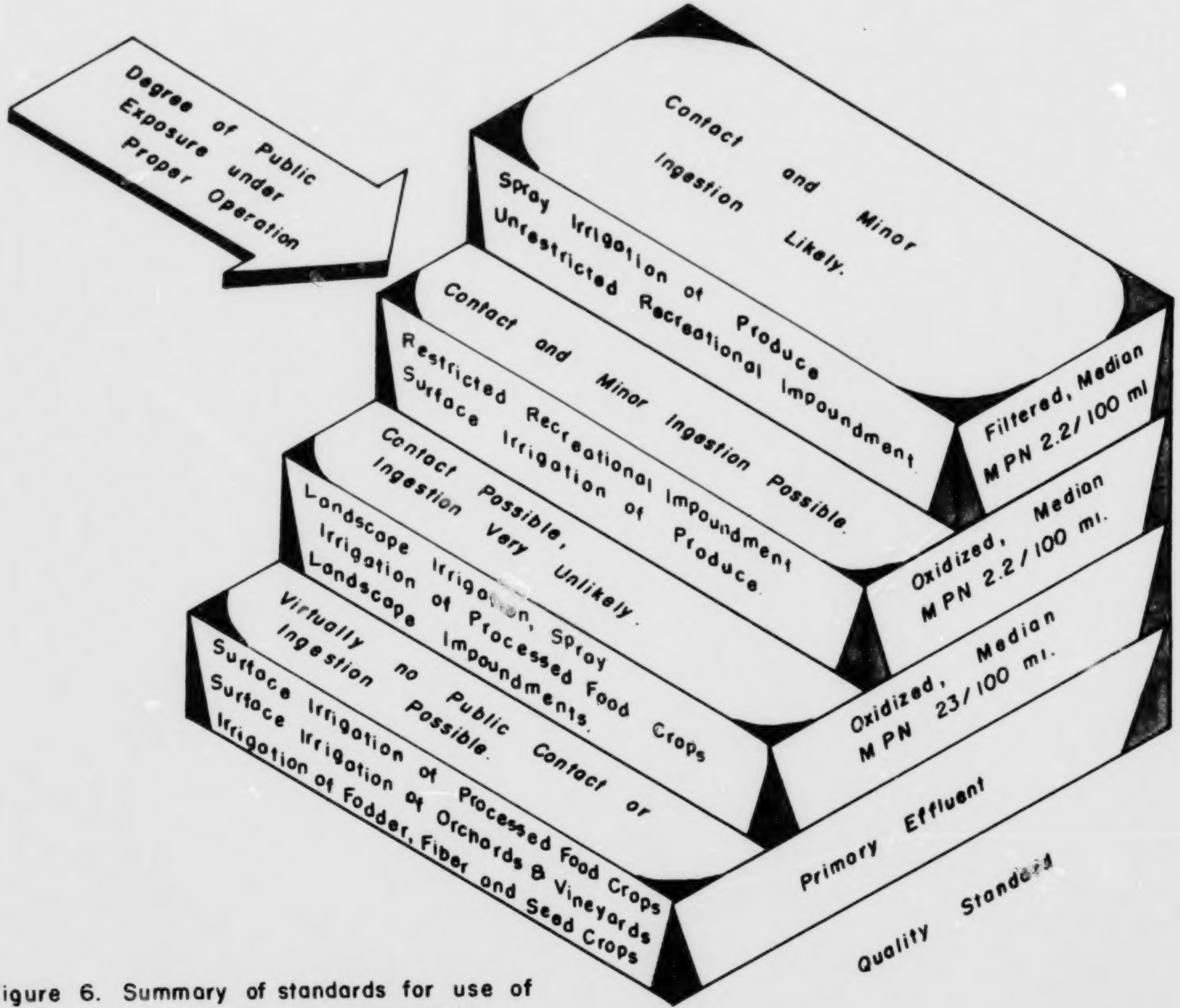
Degree of Public Exposure under Proper Operation
Contact and Minor Ingestion Likely.
Spray Irrigation of Produce
Unrestricted Recreational Impoundment
Filtered, Median MPN 2.2/100 ml
Contact and Minor Ingestion Possible.
Restricted Recreational Impoundment
Surface Irrigation of Produce
Oxidized, Median MPN 2.2/100 ml.
Contact Possible, Ingestion Very Unlikely.
Landscape Irrigation, Spray Irrigation of Processed Food Crops
Landscape Impoundments.
Oxidized, Median MPN 23/100 ml.
Virtually no Public Contact or Ingestion Possible.
Surface Irrigation of Processed Food Crops
Surface Irrigation of Orchards & Vineyards
Irrigation of Fodder, Fiber and Seed Crops
Primary Effluent Quality Standard

Figure 6. Summary of standards for use of reclaimed waste water (54)

increment" may be partly of domestic origin, concentration due to consumptive loss (normally 10-30 percent), from industrial and commercial contributions, and/or groundwater infiltration of the waste water collection system. Since the quality of any municipal water supply may vary significantly, depending upon the nature of its source as well as upon the municipal use increment, the reported chemical quality of any municipal waste water effluent may vary considerably. However, since most municipal water supplies represent water of excellent quality for irrigation use, it is generally the chemical increment picked up through municipal use that will adversely affect the quality for reuse.

In most water-short areas where reuse of water is a practical necessity there is a growing concern for controlling the magnitude of the municipal use increment by careful regulation of undesirable contributions of highly mineralized wastes. Several studies of mineral increments from community use have been made (55, 56, 57, 58, 59, 60) and examples of data reported are shown in Tables 21, 22, 23 and 24. The most important potential pollutants in municipal waste water effluents affecting an irrigation supply would include total dissolved solids, sodium, chloride, alkalinity and boron.

Characteristics of industrial waste waters. Characterization of industrial wastes is exceedingly difficult for several reasons: (a) the numerous water-using and waste-producing varieties of industries, (b) the wide range and spectrum of potential pollutants that are involved, sometimes varying significantly within the same industry, and (c) the paucity of factual data available on the volume and pollutional characteristics of many industrial wastes.

Examples of important water-using industries and associated pollutional characteristics of their waste waters are shown in Tables 25 and 26.

Potential pollutants of industrial origin that are of particular concern to irrigated agriculture include: (a) total dissolved solids, sodium, and chlorides, (b) boron, (c) heavy metals, (d) pesticides, and (e) radioactivity.

Fate of municipally and industrially derived pollutants in irrigation return flows. Certain pollutants, initially derived from the use of municipal and industrial effluents as a source of irrigation supply, reappear in the return flows in essentially the same form, but possibly in increased concentrations. Other pollutants are degraded during the course of the irrigation use to where they are no longer capable of being identified. Other pollutants may be taken up by the crops or fixed more or less permanently in the soil. Table 27 depicts the probable fate of some common pollutants occurring in irrigation supplies originating from municipal and industrial effluents.

Table 21. Average increments added by community use of water (60).

Pollutants	Overall		Eastern		Western	
	Average	Range	Average	Range	Average	Range
BOD	22	8- 45	21	8- 33	23	10- 45
COD	111	36-218	96	36-159	218	218
ABS	6	2- 10	5	2- 10	8	6- 9
Na^+	69	8-115	59	42- 98	74	8-115
K^+	10	7- 15	9	7- 12	11	7- 15
NH_4^+	19	3- 50	21	9- 29	18	3- 50
Ca^{++}	17	1- 44	24	1- 44	13	2- 30
Mg^{++}	7	0- 24	8	3- 11	7	0- 24
Cl^-	75	14-200	53	14-102	92	20-200
NO_3^-	9	0- 26	11	0- 26	7	0- 15
NO_2^-	1	0.1- 2	0.8	0.1- 2	2	2
NCO_3^-	104	-44-265	147	49-265	81	-44-247
$CO_3^=$	-1	0--10	-1	0- -5	-1	0--10
$SO_4^=$	28	10- 57	28	12- 52	29	10- 57
$SiO_3^=$	16	13- 22	15	15	17	13- 22
$PO_4^\equiv$ (total)	24	2- 50	19	2- 35	28	7- 50
$PO_4^\equiv$ (ortho)	22	7- 34	20	12- 34	25	7- 34
Hardness ($CaCO_3$)	69	10-185	95	15-151	58	10-185
Alkalinity ($CaCO_3$)	85	-35-217	121	40-217	66	-36-203
TDS	323	128-541	287	128-457	352	194-541

Table 22. Summary of mineral increments in domestic waste water for 15 California communities (56).

Analysis	Minimum range	Maximum range	Normal range domestic sewage
Dissolved solids ppm	Trace	1200	100-300
Conductivity K x 10^5	30	240	30- 60
Boron (B) ppm	.1	3.8	.1- .4
Percent sodium, percent	1	42	5- 15
Sodium (Na) ppm	30	290	40- 70
Potassium (K) ppm		22	7- 15
Magnesium ($CaCO_3$) ppm		110	15- 40
Calcium ($CaCO_3$) ppm		250	15- 40
Total Nitrogen (N) ppm	12	42	20- 40
Phosphate (PO_4) ppm	2	50	20- 40
Sulfate (SO_4) ppm		75	15- 30
Chloride (Cl) ppm	20	550	20- 50
Total alkalinity ($CaCO_3$) ppm		230	100-150

Table 23. Sources and amounts of salt pickup in two sewage systems (55).

Source of pickup	Contribution to total pickup	
	Los Angeles	
	County mg/l	City mg/l
Regeneration waters	25	-
Oil brines	640	14
Domestic use	225	356
Commercial and industrial	350	153
Seawater infiltration	-	112
TOTAL pickup	1240	635

Table 24. Comparison of tap water and sewage effluent[1] (58).

Test	Tap water sources						Sewage effluent source					
	Batavia	Dayton	Hamilton	Lebanon	Loveland	Average	Batavia	Dayton	Hamilton	Lebanon	Loveland	Average
COD-unfiltered	7.8	5.7	2.3	8.2	5.4	6.0	171	169	165	92	146	149
COD-filtered							128	114	92	78	92	101
COD-filtered, corrected for Cl^-	4.5	1.4	0.3	2.7	1.7	2.0	116	99	79	49	78	84
Anionic detergents (ABS)	0.03	0.02	0.03	0.02	0.01	0.02	10.1	7.2	6.2	4.6	9.0	7.4
Hydroxylated aromatic (tannic acid)	0.04	0.01	0.01	0.07	0.11	0.05	2.9	1.3	2.0	0.6	1.5	1.7
Carbohydrated (glucose)	0.05	0.06	0.04	0.08	0.03	0.05	2.6	2.2	5.0	1.0	1.5	2.5
Reducing sugars (glucose)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Organic nitrogen (N)	0.15	0.04	0.02	0.09	0.07	0.07	4.1	1.4	3.5	1.1	1.5	2.3
Nitrate (N)	0.03	1.41	1.18	0.08	0.62	0.67	3.1	4.9	0.2	7.8	4.6	4.1
Nitrite (N)	0.008	0.003	0.040	0.095	0.008	0.031	0.59	0.10	0.08	0.34	0.56	0.33
Ammonia (N)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	6.8	16.3	22.1	19.4	15.7	16.1
Total alkalinity ($CaCO_3$)	22	38	40	311	294	141	174	198	257	351	335	263
Calcium (Ca^{++})	20	22	12	108	96	52	63	53	54	109	97	75
Magnesium (Mg^{++})	5	11	11	30	21	15	14	21	22	33	22	22
Potassium (K^+)	2.0	2.1	2.0	1.6	1.8	1.9	13.7	9.3	11.2	9.8	11.8	11.2
Sodium (Na^+)	8.5	17.5	17.3	13.9	10.5	13.5	50	68	63	112	55	70
Phosphate ($PO_4^=$)												
Total	0.045	0.051	0.038	0.022	0.58	0.043	34.6	19.4	19.5	18.5	29.5	24.3
Ortho	0.004	0.009	0.005	0.006	0.032	0.011	33.8	17.9	18.9	15.6	27.5	22.8
Sulfate ($SO_4^=$)	56	79	56	96	53	68	95	91	108	111	99	101
Chloride (Cl^-)	11.5	16.8	9.0	22.5	15.7	15.1	51.8	67.3	49.4	124	62.0	70.9
Residue 105°C	98	177	140	520	344	256	472	525	597	648	492	547
Residue 600°C	78	149	133	368	262	198	359	380	445	526	389	420
Loss on ignition	20	28	7	152	82	58	113	145	152	122	103	127
pH	9.4	8.4	8.5	7.7	7.4	8.3	7.5	7.3	7.8	7.8	7.6	7.5
Specific conductance, micromhos/cm	193	307	236	750	622	422	730	864	796	1,185	1,003	916

[1] Table values are mg/l except pH and specific conductance.

Table 25. Some significant chemical in industrial waste waters[1] (61).

Chemical	Industry
Acetic acid	Acetate rayon, pickle and beetroot manufacture.
Alkalis	Cotton and straw kiering, cotton manufacture, mercerizing, wool scouring, laundries.
Ammonia	Gas and coke manufacture, chemical manufacture.
Arsenic	Sheep-dipping, fell mongering.
Chlorine	Laundries, paper mills, textile bleaching.
Chromium	Plating, chrome tanning, aluminum anodizing.
Cadmium	Plating.
Citric acid	Soft drinks and citrous fruit processing.
Copper	Plating, pickling, rayon manufacture.
Cyanides	Plating, metal cleaning, case-hardening, gas manufacture.
Fats, oils, grease	Wool scouring, laundries, textiles, oil refineries.
Fluorides	Gas and coke manufacture, chemical manufacture, fertilizer plants, transistor manufacture, metal refining, ceramic plants, glass etching.
Formalin	Manufacture of synthetic resins and penicillin.
Hydrocarbons	Petrochemical and rubber factories.
Hydrogen peroxide	Textile bleaching, rocket motor testing.
Lead	Battery manufacture, lead mining, paint manufacture, gasoline manufacture.
Mercaptans	Oil refining, pulp mills
Mineral acids	Chemical manufacture, mines, Fe and Cu pickling, DDT manufacture, brewing, textiles, photoengraving, battery manufacture.
Nickel	Plating.
Nitro comp.	Explosives and chemical works.
Organic acids	Distilleries and fermentation plants.
Phenols	Gas and coke manufacture, synthetic resin manufacture, textiles, tanneries; tar, chemical and dye manufacture, sheep-dipping.
Silver	Plating, photography.
Starch	Food textile, wallpaper manufacture.
Sugars	Dairies, foods, sugar refining, preserves, wood process.
Sulfides	Textiles, tanneries, gas manufacture, rayon manufacture.
Sulfites	Wood process, viscose manufacture, bleaching.
Tannic acid	Tanning, sawmills.
Tartaric acid	Dyeing; wine, leather and chemical manufacture.
Zinc	Galvanizing, plating, viscose manufacture, rubber process.

[1] Reproduced by permission Butterworths. "River Pollution. 2: Causes and Effects," Klein.

Table 2[illegible]. Summary of industrial waste: its origin, character, and treatment (61).

Industries Producing Wastes	Origin of Major Wastes	Major Characteristics	Major Treatment and Disposal Methods
Food and drugs			
Canned goods	Trimming, culling, juicing, and blanching of fruits and vegetables	High in suspended solids, colloidal and dissolved organic matter	Screening, lagooning, soil absorption or spray irrigation
Dairy products	Dilutions of whole milk, separated milk, buttermilk, and whey	High in dissolved organic matter, mainly protein, fat, and lactose	Biological treatment, aeration, trickling filtration, activated sludge
Brewed and distilled beverages	Steeping and pressing of grain, residue from distillation of alcohol, condensate from stillage evaporation	High in dissolved organic solids, containing nitrogen and fermented starches or their products	Recovery, concentration by centrifugation and evaporation, trickling filtration, use in feeds
Meat and poultry products	Stockyards, slaughtering of animals, rendering of bones and fats, residues in condensates, grease and wash water, picking of chickens	High in dissolved and suspended organic matter, blood, other proteins and fats	Screening, settling and/or flotation, trickling filtration
Beet sugar	Transfer, screening and juicing waters, draining from lime sludge, condensates after evaporator, juice, extracted sugar	High in dissolved and suspended organic matter, containing sugar and protein	Reuse of wastes, coagulation, and lagooning
Pharmaceutical products	Mycelium, spent filtrate, and wash waters	High in suspended and dissolved organic matter, including vitamins	Evaporation and drying; feeds
Yeast	Residue from yeast filtration	High in solids (mainly organic) and BOD	Anaerobic digestion, trickling filtration
Pickles	Lime water, brine, alum and tumeric, syrup, seeds and pieces of cucumber	Variable pH, high suspended solids, color, and organic matter	Good housekeeping, screening, equalization
Coffee	Pulping and fermenting of coffee bean	High BOD and suspended solids	Screening, settling, and trickling filtration
Fish	Rejects from centrifuge, pressed fish, evaporator and other wash water wastes	Very high BOD, total organic solids, and odor	Evaporation of total waste, barge remainder to sea
Rice	Soaking, cooking, and washing of rice	High in BOD, total and suspended solids, (mainly starch)	Lime coagulation, digestion
Soft drinks	Bottle washing, floor and equipment cleaning, syrup-storage-tank drains	High pH, suspended solids and BOD	Screening, plus discharge to municipal sewer
Apparel			
Textiles	Cooking of fibers, desizing of fabric	Highly alkaline, colored, high BOD and temperature, high suspended solids	Neutralization, chemical precipitation, biological treatment, aeration and/or trickling filtration
Leather goods	Unhairing, soaking, deliming, and bating of hides	High total solids, hardness, salt, sulfides, chromium, pH precipitated lime and BOD	Equalization, sedimentation, and biological treatment
Laundry trades	Washing of fabrics	High turbidity, alkalinity, and organic solids	Screening, chemical precipitation, flotation, and adsorption
Chemicals			
Acids	Dilute wash waters; many varied dilute acids	Low pH, low organic content	Upflow or straight neutralization, burning when some organic matter is present
Detergents	Washing and purifying soaps and detergents	High in BOD and saponified soaps	Flotation and skimming, precipitation with $CaCl_2$
Cornstarch	Evaporator condensate, syrup from final washes, wastes from "bottling up" process	High BOD and dissolved organic matter; mainly starch and related material	Equalization, biological filtration
Explosives	Washing TNT and guncotton for purification, washing and pickling of cartridges	TNT, colored, acid, odorous, and contains organic acids and alcohol from powder and cotton, metal, acid, oils, and soaps	Flotation, chemical precipitation, biological treatment, aeration, chlorination of TNT, neutralization
Insecticides	Washing and purification products such as 2, 4D and DDT	High organic matter, benzene ring structure, toxic to bacterial and fish, acid	Dilution, storage, activated carbon adsorption, alkaline chlorination
Phosphate and phosphorus	Washing, screening, floating rock, condenser bleed-off from phosphate reduction plant	Clays, slimes and tall oils, low pH, high suspended solids, phosphorus, silica and fluoride	Lagooning, mechanical clarification, coagulation and settling of refined waste
Formaldehyde	Residues from manufacturing synthetic resins, and from dyeing synthetic fibers	Normally has high BOD and HCHO, toxic to bacteria in high concentrations	Trickling filtration, adsorption on activated charcoal
Materials			
Pulp and paper	Cooking, refining, washing of fibers, screening of paper pulp	High or low pH; colored; high suspended, colloidal, and dissolved solids; inorganic fillers	Settling, lagooning, biological treatment, aeration, recovery of by-products
Photographic products	Spent solutions of developer and fixer	Alkaline, contains various organic and inorganic reducing agents	Recovery of silver, plus discharge of wastes into municipal sewer
Steel	Coking of coal, washing of blast-furnace flue gases, and pickling of steel	Low pH, acids, cyanogen, phenol, ore, coke, limestone, alkali, oils, mill scale, and fine-suspended solids	Neutralization, recovery and reuse, chemical coagulation
Metal-plated products	Stripping of oxides, cleaning and plating of metals	Acid, metals, toxic, low volume, mainly mineral matter	Alkaline chlorination of cyanide, reduction and precipitation of chromium, and lime precipitation of other metals
Iron-foundry products	Wasting of used sand by hydraulic discharge	High suspended solids, mainly sand; some clay and coal	Selective screening, drying of reclaimed sand
Oil	Drilling muds, salt, oil, and some natural gas, acid sludges and miscellaneous oils from refining	High dissolved salts from field, high BOD, odor, phenol, and sulfur compounds from refinery	Diversion, recovery, injection of salts; acidification and burning of alkaline sludges
Rubber	Washing of latex, coagulated rubber, exuded impurities from crude rubber	High BOD and odor, high suspended solids, variable pH, high chlorides	Aeration, chlorination, sulfonation, biological treatment
Glass	Polishing and cleaning of glass	Red color, alkaline nonsettleable suspended solids	Calcium chloride precipitation
Naval stores	Washing of stumps, drop solution, solvent recovery, and oil recovery water	Acid, high BOD	By-product recovery, equalization, recirculation and reuse, trickling filtration
Energy			
Steam power	Cooling water, boiler blowdown, coal drainage	Hot, high volume, high inorganic and dissolved solids	Cooling by aeration, storage of ashes, neutralization of excess acid wastes
Coal processing	Cleaning and classification of coal, leaching of sulfur strata with water	High suspended solids, mainly coal; low pH, high H_2SO_4 and $FeSO_4$	Settling, froth flotation, drainage control, and sealing of mines
Nuclear power and radioactive materials	Processing ores, laundering of contaminated clothes, research-lab wastes, processing of fuel, power-plant cooling waters	Radioactive elements, can be very acid and "hot"	Concentration and containing, or dilution and dispersion

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Table 27. Probable fate of municipal and industrial pollutants after irrigation.

Pollutants of Municipal and Industrial Origin	Probable Fate After Irrigation Use
Total dissolved solids Sodium Chlorides Sulfates Boron	Reappears in surface and subsurface return flows in increased concentrations (32, 40, 57, 62)
Heavy metals Phosphorus	Precipitated and fixed in soil; some may persist in surface return flow (62, 63, 64, 65)
Bacteria	Removed in soil; some may persist in surface return flow (66, 67, 68, 32, 64, 61, 69, 62)
Radioactivity	Removed in soil; taken up by crops; some may persist in surface return flow (70, 71, 72, 62)
Pesticides and exotic organic chemicals	Many removed in soil; will persist in surface return flow; some may possibly persist in subsurface return flow (73, 64, 61, 62)

Irrigation supplies from used water. In many arid and semi-arid regions of the United States, it has become increasingly necessary to use and reuse water supplies to the fullest extent possible. Municipal waste water effluents have been satisfactorily used by irrigated agriculture in many instances with few adverse effects. The use of industrial effluents has not been so widely reported, perhaps due to the more apparent inherent hazards associated with certain readily identifiable pollutional constituents. In addition, most of the major water-using industries and irrigated agriculture are not so located with respect to each other that direct reuse of industrial effluents is physically possible.

In view of current water pollution control legislation and the high degree of treatment and removal of potential pollutants being required, it appears that in the future a marked increase in the utilization of available municipal and industrial effluents for irrigation supplies in water-short areas is inescapable and may even be highly desirable.

Testing and Monitoring

Assessment of the cause and effect relationship between irrigation and water quality, as affected by irrigation return flows, is based upon the existence of adequate water quality data in time and space. Insight into the gross adequacy of such data can be provided best by means of a historical outline of water quality monitoring in the United States, with special reference to the seventeen western states.

History of water quality monitoring in western United States

Analyses of the chemical composition of natural waters in the western United States goes back to the work of Hilgard in the 1800's (74). He published results of 55 analyses from springs and wells, in relation to use of such waters for irrigation. He also published seven University of California Agricultural Experiment Station reports (75, 76, 77, 78, 79, 80, 81) which contain results of water analyses.

In 1891 a program in water quality analyses with respect to irrigation was begun at the Agricultural Experiment Station in Arizona (82). Similarly, in 1900 a water quality program was begun in New Mexico (83). In 1903, analyses were made of some Oregon waters (84) with reference to irrigation. These analyses were valuable from the standpoint of initiating programs and providing data as a reference for measuring changes.

Beginning of systematic effort for a national picture. In 1903, R. B. Dole of the U. S. Geological Survey initiated plans to systematically sample all major waters of the United States on a recurrent basis (85). This was to be done slowly and through cooperative agreements with state agencies and others. The first results were published in 1907 (86) and contained data for 92 stations scattered throughout the United States east of the one-hundredth meridian. Dole also provided an extensive treatise on methods of analyses.

Dole's work in 1909 was the beginning of systematic water quality investigations. The following year Van Winkle and Eaton (87) published the first comprehensive water quality survey of waters in California, involving 37 rivers. These rivers were sampled on a recurrent basis for one year or more. The analyses were interpreted in the context of such natural influences as climate, geologic conditions, and vegetation, of potential industrial and other uses, and of the economic significance. The effect of irrigation on mineral composition of some waters is also mentioned. Similar studies followed in Oregon (88), Washington (89) and other states.

Water quality for reclamation. The above investigations were to establish the value of various state waters as water resources per se, with some industrial orientation, and to provide a background of basic data. Other investigations were initiated by the Reclamation Service to ascertain the value of various waters for irrigation. In 1905 and 1907, Stabler (90) of the U. S. Geological Survey supervised a systematic sampling program for a 55-station network having wide coverage throughout the West. The waters chosen for sampling were those likely to be utilized by the Reclamation Service; the sampling program was to assess potential salinity and silting problems.

The various agricultural experiment stations were also active in assessing water quality with respect to irrigation, beginning with Hilgard in 1886. One of the most recent works of this nature is by Thorne and Thorne (91).

Data retrieval, initial efforts. In 1924, Clarke (85) compiled and published all known analytical data for waters of the United States with comments concerning land use and other lithologic factors relevant to the water quality characteristics of the respective waters.

In 1926, Collins and Howard published "Index of Analyses of Natural Waters in the United States" (92) which was intended to include reports of all federal and state surveys, experiment stations, health departments, and references to journal articles. This was an important landmark in that it was the first attempt to aid "information retrieval" of water quality data -- an obviously important contribution as the amount of studies proliferated, such that works similar to Clarke's (85) were no longer feasible. The publications listed in this Index are in the form of an annotated bibliography. Collins and Howard updated their Index in 1932 (93).

First permanent monitoring network. In 1931 the first permanent water quality monitoring network was established by the International Boundary Commission to monitor streams flowing into Mexico with respect to chemical, sanitary, and physical characteristics (94). Each of the major streams were monitored at several points to a considerable distance upstream and annual reports published.

Establishment of a permanent national network. The first permanent national water quality network was established by the U. S. Geological Survey in 1941. Annual records of chemical quality, suspended sediment, and water temperature have been published since 1941 (95). From 1941 to 1963 these records were published annually as water supply papers (95). By 1963 the Geological Survey maintained 419 stations on 270 streams. Samples were collected daily and monthly at 276 of these locations for chemical-quality studies.

Beginning with the 1964 water year, these records were published as a new series on a state boundary basis (96). The primary purpose of this series is to make the data available for immediate use. These same records are to be published in Geological Survey Water-Supply Papers ate five-year intervals.

Permanent network established for irrigation return flows. A major contribution to the study of irrigation return flows was initiated in 1951 with the selection of 100 permanent monitoring stations by the Subcommittee on Hydrology, Water Resources Council). In 1957 data for 82 irrigation network stations were reported in the annual water supply paper, "Quality of Surface Waters for Irrigation, Western United States" (97).

The purpose is indicated in the 1957 report: "A need was recognized for comprehensive continuing information about the chemical quality of surface waters used for irrigation and the changes resulting from the drainage of irrigated lands. In recognition of this problem, the Subcommittee on Hydrology, Interagency Committee on Water Resources on February 6, 1950, approved a list of 106 network stations on streams in western United States at which water samples were to be collected and analyzed with particular reference to the use of these stream waters for irrigation" (97).

It is significant that among the criteria for selection of network stations, two are quite relevant to today's thinking: (a) "Consideration should be given to the location of irrigation development areas that are now affecting or are likely to affect the chemical quality of the river water," and (b) "Only those stations should be proposed that are likely to reflect important changes in chemical quality over a period of years." According to Love (98), "These long-term records will assist in the determination of quality of water prior to irrigation development, the extent of impairment of water quality due to drainage return, requirements for maintaining proper salt balance, and the equitable division of water between projects, states, and adjoining nations." Discussion of salinity conditions is given for each of the major river basins in the respective annual reports (97).

Pollution-oriented national water quality network. The next major impetus in the direction of systematic water quality monitoring was the establishment of the National Water Quality Network in 1956 under Public Law 660, by the U. S. Public Health Service (99), Division of Water Supply and Pollution Control. (This activity was transferred to the Department of the Interior in 1966 as the Federal Water Pollution Control Administration.) For the initial phase of the program, 50 sampling stations were established, beginning operation October 1, 1957.

The significance of this national network is partly that it adds to the wealth of information through enlargement of the existing networks; but more important, this network was established to monitor the nation's water in terms of pollution relevance, and to provide comprehensive analyses in order to assess the expanding dimensions of the water pollution problems -- some of which are relevant to irrigated agriculture. The routine analyses include:

(a) Radioactivity (weekly).

(b) Plankton populations (monthly or semi-monthly).

(c) Coliform organisms (weekly).

(d) Organic chemicals (monthly).

(e) Biochemical, chemical, and physical measurements, including bichemical oxygen demand, dissolved oxygen, chemical oxygen demand, chlorine demand, ammonia nitrogen, pH, color, turbidity temperature, alkalinity, hardness, chloride, sulfate, and total dissolved solids (weekly).

(f) Trace elements (two-month composite of weekly samples).

Project-oriented data collection activities. The Colorado River is one of the most intensively studied streams with respect to salinity. A sampling program was begun by Collins and Howard in 1925 (100) and has continued intermittently. The data have been summarized by Iorns, et al (101). Presently, the Colorado River Basin Project of the Federal Water Pollution Control Administration maintains a sampling network for the comprehensive study of salinity in the Colorado River System. This network, operated since 1965, contains 35 stations in addition to the USGS network. Common cations and anions are measured from monthly samples.

Some western states have very modest data collection programs, others moderate, and some, such as California, extensive. Using Utah as an example, Stewart and Hirst (102) and later Greaves and Hirst (103) reported analyses of a number of irrigation waters in the state. The next activity was not until 1951 with the extensive sampling survey of Thorne and Thorne (91). In 1958 Conner and Mitchell (104) compiles results to that date of all available analyses for surface and groundwaters in Utah.

Groundwater. Monitoring activities related to groundwater have been much less systematic than activities in the surface water area. The pattern appears to consist of assessment of groundwater quality characteristics on an area-by-area basis as the need arises -- which need may be related to project investigations or to suitability for resource development.

California, through its Department of Water Resources, has had one of the most comprehensive systematic sampling programs of any state. Its plan to sample all groundwater of the state was initiated in 1952 as a cooperative program with the U. S. Geological Survey.

Data retrieval. Data availability is of parallel importance with sampling activities. A large amount of data is available through the annual reports of basic data of the U. S. Geological Survey and the Federal Water Pollution Control Administration, and from annual reports of some states. These are mostly data taken from permanent, federally operated, water quality networks. Much data are published, however, as supportive of project investigations, and some are maintained within the files of organizations only for internal use. Knowledge of such efforts sometimes requires determination to acquire.

The first attempt to facilitate data retrieval was Clarke's 1925 compilation (85) of all analyses known from all sources to 1925. Thus all data taken in the United States prior to 1925, available through normal federal, state, and local channels, were presented in his report. The next significant effort at data compilation was Iorns', _et al_ (101) report of basic data for the Colorado River.

Since nationwide and even, in some cases, basinwide all inclusive data compilations today are unfeasible as a matter of routine, inventories of data sources have been compiled. The first was that of Collins and Howard in 1926 (92), which listed all known reports containing water quality analyses, from federal, state, and other sources. This listing was updated by Collins and Howard in 1932 (93) to cover the intervening years. The next publication of this type was Bulletin 2 (104) "Inventory of Published and Unpublished Chemical Analyses of Surface Waters in the Western United States." The report was prepared by the Hydrologic Subcommittee of the Federal Interagency River Basin Committee, and agricultural use of western waters was preeminent in the thinking of the committee in sponsoring the report development. A supplement was the "Inventory of Published and Unpublished Chemical Analyses of Surface Waters in Western United States, 1947-55" Bulletin 9 (106). The next supplement was USGS WSP 1786 by Woodward and Heidel (107), which covers the period October 1, 1955 to September 30, 1961, for states west of the Mississippi River.

In 1964 the Bureau of the budget authorized (in Circular A-67) the Department of the Interior to coordinate federal activities in the acquisition of certain water data (108). Implementation of the circular became the responsibility of the U. S. Geological Survey, which established the Office of Water Data Coordination (OWDC). The OWDC undertook the preparation of a Catalog of Information on Water Data. Initially, information was listed under one of four categories, which include: water quality stations, surface water stations, groundwater stations, and results of aerial hydrologic investigations. Input to the catalog consists of information supplied by those federal agencies that acquire data either directly or in cooperation with state or local agencies. Access to the catalog is provided by OWDC through the use of indexes, such as "Index to Catalog of Information on Water Data-Water Quality Stations," 1966 ed. (108). The first catalog appears in 1966 for "water quality stations" and other volume for "surface water stations" (109).

More water quality data and related water resource data are being collected now than ever before. In addition to those collections being made by the U. S. Geological Survey, the Division of Pollution Surveillance of the Federal Water Pollution Control Administration is establishing additional water quality monitoring stations in the national network. These two agencies of the Department of the Interior are now making use of a new data storage and retrieval system named STORET. Automatic data processing provides a rapid and efficient means of storage and retrieval of data for visual examination and for further processing and analysis. STORET is part of a large integrated system designed for the storage, retrieval, processing, analysis, and reporting of water quality data. A wide variety of data may be stored in the system, and subsequently subjected to almost any desired statistical analysis for which a computer program is prepared. It is anticipated that in the near future the capabilities of the system may be expanded to include such things as municipal water treatment and waste treatment inventories, water use data, state water quality standards and implementation plans, and extended biological parameters of water quality importance.

Continuous instrumental monitoring. According to McCallum and Stierli (110), water quality instrumentation for in situ monitoring began in 1960. First, a symposium "Water Quality Measurement and Instrumentation" was held in 1960 in Cincinnati (111). This brought into focus the many facets of automated instrumentation systems for in situ water quality surveillance. The same year the PHS installed 65 battery-operated conductivity recorders at remote locations in the Arkansas-Red River basins to continuously measure salt pollution. By 1960 a commercial system also had been developed for continuous measurement of temperature, pH, specific electrical conductivity, dissolved oxygen, turbidity, and sunlight intensity (110).

The Division of Water Supply and Pollution Control, U. S. Public Health Service (now FWPCA), has provided continued stimulus in development of such automated systems. It has also provided leadership in developing specifications for operable systems (112). Private manufacturers have developed comprehensive sensing systems. One such system (line-operated) was installed in the Pautexent River in 1963 by the U. S. Geological Survey (113). This was an eight-parameter package system, with continuous recording by a multipoint analog recorder. The cost, including housing structure, was about $10,000 per station. This system required only monthly maintenance.

While the telemetry capability described above has been line-operated, the development of a battery operated sensor-telemetry system has been progressing (114), using commercially available battery-powered sensors. Presently, continuous data recording must be done by battery-operated strip chart recorders located in the field. Two such stations were established for a water quality-hydrology modeling project (115). The existence of these stations allows the evaluation and simulation modeling of diurnal variation for several parameters (dissolved oxygen, temperature, conductivity, pH). In addition, continuous monitoring permits evaluation of stochastic variations in the measured parameters. These data, coupled with conventional sampling, provide a well defined picture of the water quality characteristics of a stream.

The value of continuous monitoring with respect to irrigation return flow would have to be assessed in the light of the objectives of the sampling network and available funds. Strategic placement of such stations and judicious use of data could be of significant value in evaluating the timing of shock loads and the effects of the pollutants.

Remote sensing. The application of remote sensing and continuous monitoring of water quality changes have many possibilities for use in identifying the source and concentration of pollutants in return flow. Remote sensing, by use of infrared photography and imagery, utilizing airplanes or satellites offers some new techniques for pollution identifications. Robinove (116) reports that infrared imagery has been used in hydrologic studies. Use of this technique is illustrated by the detection of diffuse groundwater discharge having a small temperature differential from the recipient water body. The method is discussed more explicitly in terms of water pollution by Van Lopik, Rambie, and Pressman (117).

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EFFECTS OF POLLUTANTS IN IRRIGATION RETURN FLOWS ON OTHER BENEFICIAL USES

Purpose of this chapter is to relate the potential pollutants in irrigation return flows to water quality criteria and standards established for the protection of other beneficial uses, including the rationale underlying the quantitative limitations imposed on the various quality factors. Hopefully, by this comparison of irrigation return flow quality and the quality needs of other legitimate water uses, one may have a reference by which to measure the magnitude of the pollutional problems identified with irrigation return flows.

As previously delineated, certain substances found in irrigation return flows are considered to be pollutants in that when discharged into a receiving water they may adversely affect subsequent use of that water. Whether these potential pollutants actually do cause any objectionable effects will depend, in part, upon the water quality requirements of the downstream uses of these waters. Recognizing that any substance if sufficiently dilute may not necessarily be a pollutant, the nature of any adverse effects will also be dependent upon the receiving water conditions; i. e., whether a surface flow or groundwater, and the extent of any dilution and commingling. Further, the concept of water quality increment to the original water supply quality, valuable in characterizing municipal and industrial waste waters, generally is not useful for irrigation return flows due to sampling and monitoring problems associated with the diffuse nature of the return flow. Actual changes in water quality resulting from irrigation use thus are not always subject to evaluation, and in some instances are indistinguishable from water quality changes due to natural phenomena.

The principal beneficial uses of water are listed below, not necessarily in order of importance:

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(a) Municipal water supplies
(b) Industrial water supplies
(c) Fish and other aquatic life
(d) Livestock watering
(e) Recreation and aesthetics
(f) Irrigation water supplies

Quality Requirements for Municipal Water Supplies

In evaluating water quality criteria for domestic use, two conditions of the water must be considered: (a) its quality at the source of supply, and (b) its quality at the tap or point of use (118). To be suitable for domestic purposes, i. e., at the tap, the raw water supply should be of such quality that it meets the Public Health Service Drinking Water Standards (119) in all factors where absolute limits are specified, or achievable by normal water treatment technology, i. e., coagulation, sedimentation, filtration, and chlorination (61). Table 28, taken from a recent report of the National Technical Advisory Committee on Water Quality Criteria (4) suggests a list of water quality criteria applicable to surface waters used for public water supplies.

While originally applicable only to the quality of supplies used by interstate carriers and others subject to Federal Quarantine Regulations, the Public Health Service Drinking Water Standards have been voluntarily accepted by most of the states as a basis for standards used for all public water supplies. The Standards delineate the required physical, chemical, and bacterial quality for drinking water, including a considerable amount of data on sampling techniques, frequency, and methods of analysis as well as an appendix devoted to background material and rationale.

Quantitative limits

Nature of limits. (a) Mandatory: limits which, if exceeded, shall be grounds for rejection of the supply having adverse effects on health; (b) recommended: limits which should not be exceeded whenever more suitable supplies are available at reasonable cost. Substances in this category, when present in concentrations above the limit, are either objectionable to an appeciable number of people or exceed the levels required by good water quality control practices.

Physical quality. Water should not contain material offensive to the sense of sight, taste, or smell. Limits are recommended for each of the following physical factors in terms of numerical values (118):

Turbidity (silica scale).	5 units
Color (standard cobalt scale) . . .	15 units
Threshold odor number not to exceed. .	3 units

Table 28. Surface water criteria for public water supplies (4).

Constituent or characteristic	Permissible[1] criteria	Desirable[2] criteria
Physical:		
Color (color units)	75	<10
Odor	Narrative	Virtually absent
Temperature*	do	Narrative
Turbidity	do	Virtually absent
Microbiological:		
Coliform organisms	10,000/100 ml**	<100/100 ml**
Fecal coliforms	2,000/100 ml**	<20/100 ml**
Inorganic chemicals:	(mg/l)	(mg/l)
Alkalinity	Narrative	Narrative
Ammonia	0.5 (as N)	<0.01
Arsenic*	0.05	Absent
Barium*	1.0	do
Boron*	1.0	do
Cadmium*	0.01	do
Chloride*	250	<25
Chromium,* hexavalent	0.05	Absent
Copper*	1.0	Virtually absent
Dissolved oxygen	≥ 4 (monthly mean) ≥ 3 (individual sample)	Near saturation
Fluoride*	Narrative	Narrative
Hardness*	do	do
Iron (filterable)	0.3	Virtually absent
Lead*	0.05	Absent
Manganese* (filterable)	0.05	do
Nitrates plus nitrites*	10 (as N)	Virtually absent
pH (range)	6.0-8.5	Narrative
Phosphorus*	Narrative	do
Selenium*	0.01	Absent
Silver*	0.05	do
Sulfate*	250	<50
Total dissolved solids* (filterable residue).	500	<200
Uranyl ion*	5	Absent
Zinc*	5	Virtually absent
Organic chemicals:		
Carbon chloroform extract* (CCE)	0.15	<0.04
Cyanide*	0.20	Absent
Methylene blue active substances*	0.5	Virtually absent
Oil and grease*	Virtually absent	Absent
Pesticides:		
Aldrin*	0.017	do
Chlordane*	0.003	do
DDT*	0.042	do
Dieldrin*	0.017	do
Endrin*	0.001	do
Heptachlor*	0.018	do
Heptachlor epoxide*	0.018	do
Lindane*	0.056	do
Mathoxychlor*	0.035	do
Organic phosphates plus carbamates*	0.1***	do
Toxaphene*	0.005	do
Herbicides:		
2,4-D plus 2,4,5-T, plus 2,4,5-TP*	0.1	do
Phenols*	0.001	do
Radioactivity:	(pc/l)	(pc/l)
Gross beta*	1,000	<100
Radium-226*	3	<1
Strontium-90*	10	<2

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[1] Permissible criteria--Those characteristics and concentrations of substances in raw surface waters which will allow the production of a safe, clear, potable, aesthetically pleasing, and acceptable public water supply which meets the limits of Drinking Water Standards after treatment. This treatment may include, but will not include more than, the processes described.

[2] Desirable criteria--Those characteristics and concentrations of substances in the raw surface waters which represent high-quality water in all respects for use as public water supplies. Water meeting these criteria can be treated in the defined plants with greater factors of safety or at less cost than is possible with waters meeting permissible criteria.

*The defined treatment process has little effect on this constitutent.

**Microbiological limits are monthly arithmetic averages based upon an adequate number of samples. Total coliform limit may be relaxed if fecal coliform concentration does not exceed the specified limit.

***As parathion in cholinesterase inhibition. It may be necessary to resort to even lower concentrations for some compounds or mixtures.

Chemical quality. In Table 29 recommended and permissible concentrations of chemical substances are reproduced from the 1962 Drinking Water Standards. Considerations of radioactivity were included in the 1962 standards for the first time, and in general the standards require that added radiation shall not bring the total from all sources above that specified by the Federal Radiation Council.

Bacterial quality. The bacterial standards, although founded on statistical probability, represent maximum permissible rather than recommended maximum limits. In effect, these requirements limit the most probable number (MPN) of coliform organisms to one per 100 ml. of water.

Summary of Effects of Potential Pollutants in Irrigation Return Flows on Municipal Water Supplies

Quality factors

Total dissolved solids (salinity): 500 mg/l, recommended limit, due to objectionable physiological effects and taste. The increase of total dissolved solids or mineral content in irrigation return flows is one of the major adverse effects on municipal water supplies. The TDS of water is unaffected by conventional water treatment.

Hardness: 150-500 mg/l as $CaCO_3$, suggested as limit (4, 118), in view of such economic factors as cost of soap, water softening, and incidental damage. The increase of hardness in irrigation return flows is of major importance as it affects municipal water supplies. One report (33) considers increases in hardness as the most important single adverse effect contributed by irrigation return flows.

Chloride: 250 mg/l, recommended limit, due to objectionable taste. The increase of chloride in irrigation return flows may be several-fold and the resulting concentration may be above the limits in many cases. It is unaffected by conventional water treatment.

Sulfate: 250 mg/l recommended limit due to objectionable physiological affects -- laxative and taste. The readily soluble nature of sulfate compounds in natural waters and the concentration effect from irrigation use frequently cause this anion to be present in return flows in concentrations well above the 250 mg/l limit. It is unaffected by conventional water treatment.

Table 29. Chemical standards of drinking water (119).

The following chemical substances should not be present in a water supply in excess of the listed concentrations where, in the judgment of the Reporting Agency and the Certifying Authority, other more suitable supplies are or can be made available.

Substance	Concentration in mg/l
Alkyl Benzene Sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250
Copper (Cu)	1
Carbon Chloroform Extract (CCE)	0.2
Cyanide (CN)	0.01
Fluoride (F)	(See 5.23)
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate[1] (NO_3)	45
Phenols	0.001
Sulfate (SO_4)	250
Total dissolved solids	500
Zinc (Zn)	5

[1] In areas in which the nitrate content of water is known to be in excess of the listed concentration, the public should be warned of the potential dangers of using the water for infant feeding.

The presence of the following substances in excess of the concentrations listed shall constitute grounds for rejection of the supply:

Substance	Concentration in mg/l
Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.01
Chromium (Hexavalent)(Cr^{+6})	0.05
Cyanide (CN)	0.2
Fluoride (F)	See below
Lead (Pb)	0.05
Selenium (Se)	0.01
Silver (Ag)	0.05

Fluoride--When fluoride is naturally present in drinking water, the concentration should not average more than the appropriate upper limit. Presence of fluoride in average concentrations greater than two times the optimum values shall constitute grounds for rejection of the supply.

Where fluoridation (supplementation of fluoride in drinking water) is practiced, the average fluoride concentration shall be kept within the upper and lower control limits.

Annual average of maximum daily air temperatures[2]	Recommended control limits--Fluoride concentrations in mg/l		
	Lower	Optimum	Upper
50.0-53.7	0.9	1.2	1.7
53.8-58.3	0.8	1.1	1.5
58.4-63.8	0.8	1.0	1.3
63.9-70.6	0.7	0.9	1.2
70.7-79.2	0.7	0.8	1.0
79.3-90.5	0.6	0.7	0.8

[2] Based on temperature data obtained for a minimum of five years.

Sodium: May be harmful to persons suffering from cardiac, renal, or circulatory diseases (118). Since sodium salts are readily soluble, concentrations expected in return flows may be several hundred milligrams per liter.

Nitrate: 45 mg/l as NO_3, recommended limit due to possibility of intantile nitrate poisoning (methemoglobinemia, cyanosis). There appears to be conflicting opinions with respect to the importance of return flow contributions of nitrate, but many recent reports (30, 66, 120, 121, 122, 123, 124) indicate that concentrations, in the limits prescribed, are appearing in both surface and groundwater return flows. It is usually not removed by conventional water treatment.

Phosphate: Causes algae blooms, tastes and odors, slime growths, and may adversely influence the coagulation process. It is present in most return flows in sufficient concentrations that it is not limiting to aquatic plant blooms although the content in the return flow may be even less than in the irrigation water.

Turbidity: Five units are the recommended limit. The major consideration is an aesthetic one, and that of consumer acceptance. Varying turbidity must be expected in return flows, but generally turbidity is not considered a major problem. Readily removed by conventional water treatment.

Tastes and odors: A threshold odor number of 3 is recommended as a limit, but it should be limited to consumer acceptance and good aesthetics. Contributing causes of tastes in irrigation return flows may be associated with the mineral content (TDS, chloride and sulfate). Nutrients (nitrate and phosphate) found in most return flows are sufficient to support objectionable aquatic growths and are indirectly responsible for tastes and odors Decomposition products of organic debris in return flows may also contribute. The problem may be further aggravated by chlorination.

Color: Recommended limit is 15 units. Consumer acceptance and aesthetics again are the major considerations. Generally, an increase in color is noted in surface return flows. However, the problem is not of major importance. Conventional water treatment will adequately reduce color.

Coliform organisms: Less than 1/100 ml is mandatory limit for protection of public health. The presence of coliform organisms in return flows may result from a variety of coliforms of soil origin or municipal and industrial effluents present in the original supply. In either case, generally no problem occurs in the subsurface return flows due to the excellent removals by the soil mantle. Significant coliform concentrations may persist in surface return flows, but limited data indicate that they are usually within the removal capability of conventional water treatment.

Temperature: Increased temperature adversely affects palatability, and accentuates tastes and odors. Limited data suggest that there may be a slight increase in temperature associated with surface return flows and that there may be a slight decrease in subsurface return flows.

Pesticides: No limits established but the objective is to have none. An indirect measure of carbon chloroform extract at 0.2 mg/l is a guide. Toxicity, taste and odor are key considerations. There is nothing conclusive on this subject yet. Perhaps the problem is summarized best by recent FWPCA report (40):

> Numerous studies have shown that repeated application of pesticides, particularly of the chlorinated hydrocarbons, has resulted in residues of some of these compounds being found in soil layers corresponding to plow and cultivation depths. These compounds are generally resistent to biological degradation. The extended persistence of these coupounds has increased the chance of water contamination. Current knowledge as to the extent and amount of pesticide residues in water resources is meager, and knowledge about the significance of these residues and their effect on water supplies even more so. The committee which reviewed and updated the USPHS Drinking Water Standards in 1962 concluded that the information available at that time was not sufficient to establish specific limits for pesticidal chemicals in drinking water. Only the concentration that will produce a perceptible odor in water has been determined for several pesticides (Table 30).
>
> A study conducted by FWPCA personnel at the Taft Sanitary Engineering Center assessed the effect of various treatments on concentrations of dieldrin, endrin, lindane, DDT, 2, 4, 5-T, and parathion from water. The study indicated that, while each part of the treatment plant may have potential for reducing certain pesticides, no effective practical treatment is known for large volumes of water containing pesticides.

Table 30. Threshold odor concentrations of pesticides and solvents in water (40).

Pesticides	Threshold Odor Concentration in ppm
Parathion (technical grade)	.003
Parathion (pure)	.036
Endrin	.009
Lindane	.330
Formulation components	
Sulfoxide (synergist)	.091
Aerosol OT (emulsifier)	14.600
Commercial Solvents:	
Deodorized Kerosene	.082
Solvent 1	.016
Solvent 2	13.900
Solvent 3	.090

Source: U. S. Department of Agriculture report prepared for FWPCA.

General discussion

The water quality factors in irrigation return flows considered of most significance to municipal water supplies are total dissolved solids, chlorides, sulfates, and hardness. While technology is available to remove or reduce the concentrations of these constituents, only hardness is capable of being removed by what is currently considered conventional water treatment processes within the range of economic feasibility. (There may be a slight reduction of TDS result from hardness removal.)

Quality factors considered of secondary significance, primarily because their effects are presently difficult to assess, are nitrates, phosphates and pesticides. Again, removal of these constituents is not effective by conventional treatment means.

Evidence indicates that the remainder of the potential pollutants discussed in this section are not serious water quality degradation factors for municipal use, either because of their low concentration and intensity or ease of removal by conventional treatment.

Quality Requirements for Industrial Water Supplies

By far the most varied spectrum of quality requirements of beneficial users is found in industrial water needs (61). Water is used as an ingredient with other raw materials in the finished product, as a buoyant transporting medium, as a cleansing agent, as a coolant, and as a source of steam in heating and power production.

Two examples of industry's varied water quality requirements are presented in Table 31 which summarizes preferred quality limits for certain process waters, and in Table 32 which reports quality characteristics of raw waters used as sources of supplies by various industries. It is impossible to organize into a single set of standards the quality requirements of water used for each of the many different industrial processes. Such quality requirements differ far too much to allow any broad generalization or simplification (118). Further, quality requirements within the same industry may vary considerably, depending upon the technology utilized.

Von Frank and Fawcett (125) point out that water used for cooling accounts for about 90 percent of the total supply withdrawn by the manufacturing and thermal-electric power industries combined, yet despite this massive use quality criteria for industrial cooling waters have received relatively little attention. This lack of rigorous criteria for industrial cooling water is, perhaps, not surprising when one views its wide variety of supply.

Regarding the lesser quantities of process waters used by industry, Partridge (125) states:

> The quality of water adequate for use in specific process operations throughout industry ranges from untreated surface water carrying pollution from natural, municipal, or industrial sources to completely demineralized water. A similar broad spread is found within many individual plants with varied process steps.
>
> To write general criteria for industrial process water representing other than the lowest common denominator accordingly seems useless. The minimum conditions applicable to all waters at all places at all times of the Ohio River Valley Water Sanitation Commission (ORSANCO) provide an example of such general criteria seasoned by 17 years of experience.

Table 31. Preferred limits for several criteria of water for use in industrial processes (125).

	Turbidity, max	Color, max	Taste and odor, max	pH		Dissolved	
				min	max	Solids, mg/l max	Oxygen, ml/l
Aluminum (hydrate wash)						low	
Baking	10	10	low				
Boiler feed							
0 to 150 psi	80			8.0		3000	<2
150 to 250 psi	40			8.4		1500	<0.2
250 to 400 psi	5			9.0		2500	0
400 to 1000 psi	2			9.6		50	0
> 1000 psi						<0.5	<0.05
Brewing	10	15	low	6.5	7.0	1500	
Carbonated beverages	2	10	low				
Confectionery			low	7.0		100	
Dairy		none	none			500	
Electroplating and finishing, rinse						low	
Fermentation	low		low				
Food canning and freezing	10		low	7.5		850	
Food processing, general	10	10	low				
Ice manufacturing						170 to 1300	
Laundering				6.0	6.8		
Malt preparation			low				
Oil well flooding				7.0			
Photographic process	low	low					
Pulp and paper							
Groundwood paper	50	30				500	
Soda and sulfate pulp	25	5				250	
Kraft paper							
bleached	40	25				300	
unbleached	100	100				500	
Fine paper	10	5				200	
Sugar manufacture						low	
Tanning operations	20	100		6.0	8.0		
Textile manufacture	0.3	0					
	25	70					

Note: The values in this table are derived from summaries in the comprehensive review by McKee and Wolf. They should be used only after study of these summaries and of the original references cited in them.

Table 32. Summary of specific quality characteristics and raw waters that have been used as sources for industrial water supplies (4).
(Unless otherwise indicated, units are mg/l and values are maximums. No one water will have all the maximum values shown.)

Characteristic	Boiler Make-up Water		Cooling Water				Process Water							
			Fresh		Brackish [2]									
	Industrial 0-1500 psig	Utility 700-5000 psig	Once-Through	Make-up Recycle	Once-Through	Make-up Recycle	Textile Industry SIC-22	Lumber Industry SIC-24	Pulp & Paper Industry SIC-26	Chemical Industry SIC-28	Petroleum Industry SIC-29	Prim. Metals Industry SIC-33	Food & Kindred Products SIC-20	Leather Industry SIC-31
Silica (SiO_2)	150	150	50	150	25	25			50		50		In general, the quality of raw surface supply should be that prescribed by the NTA Committee on Water Quality Requirements for Public Water Supplies.	
Aluminum (Al)	3	3	3	3										
Iron (Fe)	80	80	14	80	1.0	1.0	0.3		2.6	5	15			
Manganese (Mn)	10	10	2.5	10	0.02	0.02	1.0			2				
Copper (Cu)							0.5							
Calcium (Ca)			500	500	1,200	1,200				200	220			
Magnesium (Mg)										100	85			
Sodium & Potassium (Na+K)											230			
Ammonia (NH_3)														
Bicarbonate (HCO_3)	600	600	600	600	180	180				600	480			
Sulfate (SO_4)	1,400	1,400	680	680	2,700	2,700				850	570			
Chloride (Cl)	19,000	19,000	600	500	22,000	22,000			200 [1]	500	1,600	500		
Fluoride (F)											1.2			
Nitrate (NO_3)			30	30							8			
Phosphate (PO_4)		50	4	4	5	5								
Dissolved Solids	35,000	35,000	1,000	1,000	35,000	35,000	150		1,080	2,500	3,500	1,500		
Suspended Solids	15,000	15,000	5,000	15,000	250	250	1,000	[3]		10,000	5,000	3,000		
Hardness ($CaCO_3$)	5,000	5,000	850	850	7,000	7,000	120		475	1,000	900	1,000		
Alkalinity ($CaCO_3$)	500	500	500	500	150	150				500		200		
Acidity ($CaCO_3$)	1,000	1,000	0	200	0	0						75		
pH, units			5.0-8.9	3.5-9.1	5.0-8.4	5.0-8.4	6.0-8.0	5-9	4.6-9.4	5.5-9.0	6.0-9.0	3-9		
Color, units	1,200	1,200		1,200					360	500	25			
Organics														
Methylene blue active substances	2 [4]	10	1.3	1.3		1.3								
Carbon tetrachloride extract	100	100	No floating oil	100	No floating oil	100						30		
Chemical oxygen demand	100	500		100		200								
Hydrogen sulfide (H_2S)					4	4								
Temperature, °F	120	120	100	120	100	120			95 [5]			100		

[1] May be $\leq$ 1,000 for mechanical pulping operations.

[2] Water containing in excess of 1,000 mg/l dissolved solids.

[3] No large particles $\leq$ 3 mm diameter.

[4] One mg/l for pressure up to 700 psig.

[5] Applies to bleached chemical pulp and paper only.

Note: Application of the above values should be based on analytical methods in ASTM Manual on Industrial Water and Industrial Waste Water (2) or APHA Standard Methods for the Examination of Water and Waste Water (1).

These minimum conditions essentially state that such waters shall be free from objectionable settleables, floatables, toxic substances, color, odor, and other nuisances. Beyond such minimums are the criteria established by industry for specific operations.

In conclusion, industry likely will continue to treat available water supplies in accord with specific needs. Fortunately, water treatment technology available today permits use of a water supply of almost any quality to produce water suitable to a given industrial use, and while the cost of such treatment may be high, it is usually a small part of the total production and marketing costs (4).

Effects of Potential Pollutants in Irrigation Return Flows on Industrial Water Quality Requirements

It would be difficult to concisely relate the effects of potential pollutants in irrigation return flows to industrial water quality requirements. However, a qualitative evaluation follows:

Potential Pollutants	Effects
Total dissolved solids Hardness Chlorides Sulfates Sodium Alkalinity	Affect many industrial uses adversely and probably have the most significant effect due to irrigation return flows. Removal by special treatment is possible, although costly.
Nitrate Phosphate Tastes and odors	May be responsible for the development of algal growths and bacterial slimes which can adversely affect cooling water use in particular, as well as process waters such as used by the food and drink industries. Effects can be controlled by conventional treatment.
Turbidity Color	Objectionable for many industrial process waters, but readily removed by conventional treatment. Not significant to cooling water use.
Temperature	Not significant.
Coliform organisms	Little indication of any serious effects on process water uses, although a potential problem could exist. Probably of no significance to cooling water use.

Effects of Return Flow on Fish and Wildlife

The problem is complex. It involves not only changes in water quality, but changes in quality of the ecological system affected. The environment includes a given water flow, light, temperature, and water quality regimen. A change in any of the four qualities can produce an effect on the aquatic biota. If the diversion for irrigation is a significant portion of the stream flow, the effect of the reduced flow on the biota below the diversion is immediate and significant. The environment is changed; therefore, the life adapted to the previous conditions must be changed. In the case of an irrigation storage dam, the impounded water greatly changes the quality of that environment in addition to changing the volume of flow in the stream channel below. Below the dam there may be a more even flow. Before dam construction, the channel may have varied from flood flow to dry bed. Above the dam a lake-type environment replaces a stream environment.

Should the source of irrigation waters be from a hydrologic system other than the system in which the receiving waters are located, the changes which could occur in the receiving waters still apply, and in addition, the changes in quality represented by the differences between the source waters and the receiving waters from the two separate systems is also a fact which must be considered. Whether irrigation practices involve a single watershed or several watersheds, there can be a marked effect of those practices on an ecological system in the receiving waters.

All factors of irrigation practice should be considered in assessing the effect of irrigation return flow on an ecosystem. For example, water diversion on a rainbow trout stream may alter the stream below the diversion from an ideal rainbow trout stream to one more suited to brown trout. The return flow would have an effect on whatever system developed in the receiving waters in place of the rainbow trout system Diversions may upgrade water quality below the structure. The Flaming Gorge Dam, for example, changed the quality of Green River from sediment-laden water suitable only for minnows and suckers to clear water suitable for rainbow trout.

Organisms respond to singular qualities in the water and also to combinations of these qualities (126, 127). For example, chlorides may act synergistically with fluorides to produce an effect on fish that neither chloride nor fluoride produces alone (126). The effect of calcium on the toxicity of boron, zinc, and copper is well documented (118, 128, 129).

Chemical effects

Different concentrations of various compounds or elements will affect different wildlife species as well as individuals within the species in a variety of ways. Also, the concentration of a given chemical quality required to produce a toxic or lethal effect on the adult of a species may be considerably more than the concentration required to produce the same effect on the young of that species. Among the invertebrates, different stages in the life cycle are differentially susceptible.

As Eldridge (33) observes, so many factors influence the effects of water constituents on aquatic life that a concise statement of specific requirements is impossible. Adverse water quality may interfere with the migration of fish, kill them, create pathological conditions, interfere with spawning, or with the production of an adequate food supply. Of the compounds listed as significant in irrigation return waters, only the compounds of boron, fluorine, sulfur, and iron occur in concentrations sufficiently great to be toxic to fish or to other components of the aquatic ecosystem. Of the elements, the heavy metals which for the most part appear as trace elements are universally toxic to both plants and animals when sufficiently concentrated. Zinc, for example, is toxic to fish in concentrations as low as 0.3 mg/l; lead in concentrations as low as 0.1 mg/l; silver as low as 0.005 mg/l.

An increase of the calcium concentration when return flow mixes with receiving waters may affect the essential carbonate buffer system, resulting in pH changes. Rapid changes in pH cause losses in the eggs and fry of fish (130). Unbalancing the carbonate buffer system may also reduce the carbon available for plants, particularly algae in the aquatic system; thus, primary productivity can be reduced (4). Boron may also occur in amounts toxic to vascular plants in the aquatic system (128).

Both nitrate and phosphate concentrations may be affected by irrigation return waters. Thorne and Thorne (91) present data indicating that decreases may occur. Since nitrates and phosphates serve as nutrients, particularly in the production of plants, either enrichment or deprivation can yield startling results on the plant communities in streams or lakes. Increased production may have deleterious effects on the habitat and food organisms of fish. High levels of these nutrients favor growth of Sphaerotilus, algae and rooted aquatic plants (131).

Little data indicate that organic loading is increased significantly as a result of irrigation return flows. However, when organic loading is increased, it also can serve as a nutrient. Organic material has a direct effect on the production of such bacteria as Sphaerotilus which are nourished directly on dissolved organics. An increase in plant production in streams tends to clog streams with plant material and debris. Subsequent oxidation of plant material decreases oxygen concentration in water (132). Once oxygen concentration is reduced in streams, decomposition of organic material produced by the enrichment will continue anarobically and may result in release of such noxious gases as hydrogen sulfide, which is toxic to a variety of aquatic organisms (133).

Increased production of plant material may result in production of certain species of algae which produce toxins as secretions that may be toxic to invertebrates and vertebrates alike (33). Invertebrate population in streams are changed in diversity by rapid growth of certain algae. Many invertebrates are sensitive to decreases in dissolved oxygen concentration in the water; and where nutrient enrichment has increased organic production, decrease in oxygen concentration is not uncommon. When such change occurs in the environment, the invertebrates with high oxygen requirements are eliminated from the system and replaced by invertebrates of lower oxygen requirement, thereby changing the ecological system and affecting the species feeding upon the invertebrates.

This effect of enrichment on the animal community also occurs among plants. Enrichment induces changes in the production of plant materials including algae, and as a consequence, dominance in the planktonic algaes. Enrichment also encourages growth of rooted, vascular aquatic plants.

Optimum range of nitrate concentration for aquatic plant production is between 0.9 and 3.3 mg/l; for phosphate between 0.9 and 1.8 mg/l (134). Thorne and Thorne (91) show phosphate concentrations in the irrigation waters of Utah to range between 0.2 and 0.6 mg/l. Nitrates above 17 mg/l may cause inhibition of chlorophyll formation (134).

Pesticide effects

Toxicity of pesticides depends on many different environmental factors, all of which vary considerably in irrigation return flows. These include temperature, pH, the amount of silt present, calcium, magnesium, the species involved, age of organisms, and other pesticides present (130).

Pesticides are concentrated in particulate matter or detritus and utilized as food by the invertebrates. Once invertebrates feed on this detritus, the pesticides are concentrated. Concentrating effects up to 10,000-fold have been found in some invertebrates. Lethal levels of all pesticides have been established and are presented in Water Quality Criteria (118) and in the Report of a Committee on Water Quality Criteria (4). Even in extremely low concentrations, pesticides affect all levels of the ecosystem and sublethal doses produce deleterious effects. Fish and other wildlife have been killed by pesticides reaching streams from sprayed areas (135, 136). Residues of pesticides have been found in most organisms examined (137). Keith and Hunt (135) observe that fish exposed to residues in water absorb pesticides directly through their gills or/and skin; or if residues are present in feed, the pesticides are ingested.

Chlorinated hydrocarbons are very resistant to degradation. Heptachlor, for example, was detected 25 months after application (130). Dilution of chlorinated hydrocarbons apparently is not an adequate means of avoiding adverse effects in the aquatic environment. Since the chlorinated hydrocarbons are long-lived, they can persist in the environment in diluted quantities; and eventually they may be concentrated in animal tissues (46).

At sublethal levels, pesticides may produce toxic effects on fish that affect the population's viability, and it is possible that pesticides may also affect enzyme activity and cell permeability within the cells of organisms. Thus, the transfer of nutrients into and within the organism may be greatly influenced by pesticide-caused damage. Eldridge (33) observes that the frequency and amplitude of electrical output of certain fish were reduced by pesticides in general. Sublethal levels of toxaphene were observed to produce effects on fish which resulted in heightened responses to external stimuli, hypersensitivity, and certain behavioral changes (138). Dieldrin reduces predation on young of guppies by the adults, and other changes in their feeding habits (130). Prolonged exposure to low doses of dieldrin causes lowering of resistance to disease (139). It also increases excitability and respiratory difficulties in fish (130). Low doses of DDT interfere with the normal thermal acclimation mechanism of fish (140). DDT tends to collect in fat of eggs of developing fish where it produces no effect until such time as the yolk materials are absorbed (141). The DDT then is released, having a lethal effect on the young fry, and it is inferred that the viability of sperm is reduced in males receiving sublethal doses.

A second class of pesticides are the organophosphates, which are highly toxic, but less resistant to degradation. Parathion is lethal to bluegills at concentrations as low as 0.2 mg/l and to cutthroat trout at 0.1 mg/l. If exposure to the pesticide is transitory or momentary, the fish can recover; however, it does take a relatively long time --

as long as three weeks to return to normal (46). Certain herbicides are very toxic to invertebrates. Diquat is particularly toxic to cladocerans. DDD has a low toxicity for fish, but very high for chironomids (130).

Among plants, dieldrin is rapidly absorbed by aquatic algae, where it is concentrated. Since algaes in the aquatic system are the base of the food chain, they are a constant source of contamination. Dieldrin also tends to affect the plants' physiology. For example, 93 mg/l over a 24-hour period affected the respiration of algae (142). Apparently many pesticides are concentrated by plants and invertebrates in aquatic systems and thus provide a constant source of contamination in higher levels of the food chain, such as fish (135).

Osmotic effects

All salts in solution, as well as any dissolved organics, contribute to osmotic concentration in the return flow. Since virtually all aquatic organisms are hoeosmotic, the amount of work required by these organisms to maintain their osmotic balance is altered with changing osmotic concentrations in water. The effects of changes in osmotic concentrations in water on respiration of fish are not clearly understood, although changes do occur (130). Less than 1,000 mg/l salts in drain water has little effect on fish and wildlife (21). Yet changes as small as 20 mg/l limit the growth of certain plant species (4). Christiansen and Low (143) observed that germination, growth, seed and tuber production decreased as salinity increased. Substantial reductions in growth were observed at substrate levels exceeding 12 mmhos. Fresh water produced the best growth in all plants with the exception of the Sago Pond Weed tubers which showed greatest growth in slightly saline conditions (3,000 mg/l). Miller (21) lists salt tolerances for several species of aquatic plants: up to 7,000 mg/l for Sago Pond Weed, 9,000 mg/l for Horned Pond Weed, 45,000 mg/l for Widgeongrass, 80,000 mg/l for Shoalgrass. Chapman (144) indicates a similar relationship with osmotic concentrations for aquatic plants throughout salt marshes and salt deserts of the world. Bolen and Ungar (146) add that as salt concentrations increase, greater competition is offered by halophytic plants.

It is apparent that any increases in osmotic concentrations of water will result in changes of metabolic rates of organisms. Since plants and invertebrates exhibit limits to their euryhalinity, changes in the structure of the community can occur. The base for production can thus change and the quality of production of the entire system can also change. This may result in changes of fish species and production.

Sediment effects

Where surface irrigation return flows are common, the sediment load may be periodically high (33). The effect of diversion structures, particularly dams, is to serve as settling basins for sediments and stabilization of stream flows below the structure, resulting in reduced corrosive action and a consequent reduction in sediment load. Where it occurs the effect of silting or sediment loads in waters can be marked on aquatic populations.

Tebo (147) observed 50 percent egg mortality in silt-covered gravel, as opposed to clean gravel. The effect of sedimentation on spawning beds is essentially to limit circulation of clean water about the eggs, with a consequent mortality or pathological condition (133). In larger fish, the silt or sediments tend to abrade and coat or clog gills of many species. This results in suffocation or an increase in the probability of secondary infections (148, 149). In migratory species, such as the salmon and the steelhead trout, streams with excessive silt tend to repel fish migration (133).

Cordone and Kelley (140) also observed that 41 to 63 percent fewer invertebrates were found in silty streams than in clear streams. The invertebrates were either smothered or destroyed by molar action. Larvae of the invertebrates are prevented from attaching to the bottom, and in silty streams may be carried away more rapidly during flood stages than in streams where rocks provide shelter. The effect of sedmients on algae and rooted plants is one of destruction by molar action. Sediments on underwater plant parts also exclude gaseous exchange with water (150). Sediments also reduce light penetration in water. The reduction of light results in disruption of the photosynthetic reaction and the production of plant materials. Any organic compounds and nutrients carried from sediment-laden waters to clearer waters downstream may encourage algae blooms (151). Even low amounts of silt for short periods of time may adversely affect primary productivity of streams (133).

Temperature

Depending upon the area, the temperature of return flow water may be several degrees centigrade greater or lesser than the source water. There is a marked effect of temperature changes on fish and other aquatic organisms. Fish adapted to cold water are unable to adapt to sudden increases in temperature, because of a thermal shock which causes behavioral changes and a general increase in lethargy. Fish are often disoriented, which may influence their migration (152). Changes occur in metabolic rates and oxygen consumption. Huet (153) notes an increased oxygen requirement for fish subjected to rapid changes in temperature.

Temperature changes may cause changes in timing of the stages of development as well as in reproduction of fish, causing a feed problem and increased mortality. In addition, eggs and fry have far narrower optimum range for temperatures than does the adult fish (152).

Life cycles of the invertebrates are often coltrolled by temperature variation. Certain species reproduce, hatch, pupate, and emerge at specific temperatures. There is also a minimum temperature requirementfor many species during the winter months so that their life cycles can be completed. Increase in water temperature in early spring may cause emergence when air temperature is too cold for survival of the adults (152).

An increase in ambient temperature may induce changes in plant species dominance. When this occurs, a change in the base of the food chain occurs and the entire system is again affected either qualitatively or quantitatively. Temperature also causes a physical effect on the environment in terms of gas solution. This is particularly serious with oxygen and carbon dioxide concentrations, for as temperatures increase the dissolved gases decrease.

Interaction effects

As Eldridge (33) points out, the complex relationship of aquatic life to irrigation return flow waters is such that it is difficult to assess effects without resorting to in situ bioassay efforts. Interactions between chemical and physical qualities can affect individuals within an ecosystem as well as the system itself.

The toxicity to fish of such elements as boron, copper, zinc and other heavy metals is affected by the calcium and magnesium concentration in waters (118). Neuhold and Sigler (126) and Huet (154) report that chlorides in water decrease the toxicity of fluorides to rainbow trout, and that soluble calcium in water likewise/decreases the toxicity of fluoride. Katz et al (130) observed that increasing acidity tends to increase the toxicity of heavy metals to aquatic organisms. The toxicity of many pesticides is also influenced by the pH and the calcium and magnesium present (130). Street et al (127) observed that rainbow trout can tolerate dieldrin in higher concentrations when DDT is present.

Chemicals in the environment also interact with physical qualities to produce quite different effects. The toxicity of any of the chemicals is related to the temperature. As temperatures increase, generally the toxicity increases because of an increased metabolism of the organisms (162). Silt and organic matter affect pH and oxygen levels in water and thereby produce an effect on the system or/and on individuals within the system. The presence of silt at times increases the toxicity of certain of the heavy metals (133). The toxicity of heavy metals is influenced by temperature and also by dissolved gases in water (155). Increases in nitrates and phosphates produce plant materials, which in turn reduce the light penetration and, upon senescence and decay, utilize oxygen in the water, resulting in a subdued light environment that is basically anaerobic in nature.

Water temperature influences the solubility of various chemicals. As temperature of the water increases, many of the salts become more soluble, thereby increasing the amounts which might be absorbed by aquatic organisms. Physical interactions which are important to the existence and functioning of an aquatic ecological system may also occur.

Interaction effects should be an extremely important part of any study of irrigation return flow effects on fish and wildlife. This is perhaps why in situ bioassay techniques have been about the only techniques effectively employed in the measurement of the effects of irrigation return flow on aquatic organisms.

Water Quality Requirements for Aquatic Life

Pertinent requirements for maximum fish production have been published (4, 32). These include: temperatures of 60° to 68° F; hydrogen ion concentration from 6.7 to 8.6; dissolved oxygen concentration above 5 mg/l; specific conductivities at 25° C; 158 to 500 micromhos or 1,000 to 2,000 micromhos in alkaline areas; dissolved solids up to 3,000 mg/l, providing that none are toxic and all are physiologically balanced; suspended solids or turbidity such that the millionth intensity level for light will not be less than five meters; carbon dioxide not above 30 mg/l; ammonium not over 1.5 mg/l; DDT concentrations less than 0.1 mg/l; fluorides not over 100 mg/l; nitrates and phosphates not toxic; calcium, magnesium, sodium, sulfate, and chlorides apparently not toxic in normal conditions.

The Committee on Water Quality Criteria (4) excludes all settleable material and limits the turbidities in warm water streams to not over 50 Jackson Units, and in cold water streams to not over 10 Jackson Units. Total dissolved solids are not to exceed 1,500 mg/l sodium chloride equivalents. Calcium must not increase enough to precipitate the carbonate, thus unbalancing the carbonate buffer system. Zinc is not to exceed 0.01 of the 96-hour TLm if the zinc concentration is continuous; copper, not more than 0.1 of the 96-hour TLm or 1/30 of the TLm for 24 hours; pH must not go below 6 or above 9. Phosphates are not to exceed 100 mg/l in streams. Pesticides are to be 0.1 to 0.01 of the 48-hour TLm in streams. Maximum allowable temperatures are 93° F for catfish and 80° F for catfish eggs; 68° F for salmonids, 55° F for salmonid eggs. Dissolved oxygen requirements for streams should never be below 7 mg/l for spawning or 4 mg/l when fish are not spawning, and this level only for short periods. Cold streams must be near saturation if eggs and fry are to develop.

Presumably if the criteria suggested by Eldridge and by the Committee for Water Quality Criteria are met, no serious effects will occur on the fish and wildlife in the area. These criteria, however, appear to be developed for fish and are not oriented to the ecosystem. It is quite possible that the minimum levels which are presented could still produce significant effects on the production within any given system. Conversely, the levels mentioned may be transversed in either direction without producing significant changes in the ecosystem. The levels listed here may be a reasonable reference but not inflexible.

Water Quality Requirements for Farmstead and Livestock

Where water on farmsteads is used in the household and/or for washing dairy equipment, etc., it should meet drinking water standards. Ideally, water for livestock would also meet these standards. It is generally recognized, however, that animals are exposed to many pollutants and it is not practical to attempt to provide water that meets all the standards for potable water.

Of the many possible pollutants in water, those associated with return flow from irrigation seem to be limited to the general soluble salts and nitrates in subsurface drainage waters. Seldom, if ever, would the nitrate in drainage waters exceed the limit for animals. Drainage from surface flow may, in addition to the above, contain pathogenic organisms and pesticides, with the pesticides possibly originating as a result of irrigation agriculture. These would appear in the water only sporadically.

Quality for livestock

The tolerance of animals to salt and other pollutants in water depends on many factors, such as species, age, physiological condition, content of the feed, as well as the kinds and amounts of salts. Apparently animals can tolerate more salt than can humans and vary in tolerance to different substances. There is also evidence that they can within limits adjust to saline waters. The general quality requirements are reviewed and discussed in publications (4, 61, 118).

A tentative guide for evaluating the quality of water for livestock is given in Table 33. McGauhey (61) reports his conclusions for salt tolerance:

> Indications are that the maximum concentrations of salts that can be tolerated by domestic animals without danger of injury by osmotic effect lie between 15,000 and 17,000 mg/l. However, a value of 10,000 mg/l is more realistic for sheep and perhaps 7,000 mg/l for milk cows in production. Obviously, these values are considerably higher than can be tolerated in humans.

The Committee on Water Quality Criteria (4) concluded that in nearly all cases the decisive factor affecting suitability is the amount of sodium, potassium, magnesium, and calcium, and that the adverse effects are roughly proportional to the total of these minerals in excess of 1,000 mg/l.

Because plants may supply enough nitrate to poison animals, low concentrations of nitrate in the water are recommended. There seems to be no general agreement as to the acceptable maximum. After an extensive review of literature (61), a range of 200 - 400 mg/l was suggested.

Pesticides are largely absorbed by soils and do not pass through soil with the leaching waters. It is possible to get toxic amounts in the return flow from surface drainage. More likely sources are accidental contamination of water supply by spillage, washing of equipment, discharge of a surplus, and from applied materials falling into waterways. It is reported (4) that to date no recorded example has been found of toxicity to livestock due to pesticide contaminants in water supplies in general.

Even if specific toxic limits were established for all animals and for each pollutant, the assay problem for continuing surveillance would be considerable for each water source inasmuch as the toxicants would likely occur only at sporadic intervals. It is suggested (4, 118) that the presence of fish in a source of water for livestock may be an excellent protective measure of toxicity, for evidence indicates that fish have a lower tolerance to various pesticides than does livestock.

Table 33. Guides to the quality of water for livestock (61).

Quality Factor mg/l	Threshold[1] Concentration	Limiting[2] Concentration
Total dissolved solids (TDS)	2500	5000
Cadmium	5	-
Calcium	500	1000
Magnesium	250	500
Sodium	1000	2000
Arsenic	1	-
Bicarbonate	500	500
Chloride	1500	3000
Fluoride	1	6
Nitrate as NO_3	200	400
Nitrite	none	none
Sulfate	500	1000
Range of pH	6.0-8.5	5.6-9.0

[1] Threshold values represent concentrations at which poultry or sensitive animals might show slight effects from prolonged use of water. Lower concentrations are of little or no concern.

[2] Limiting concentrations based on interim criteria, South Africa. Animals in lactation or production might show definite adverse reaction.

[3] Total magnesium compounds plus sodium sulfate should not exceed 50 percent of the total dissolved solids.

Quality Requirements for Recreational and Aesthetic Uses of Water

Recreational uses of water as herewith discussed refers primarily to water contact activities including swimming, wading, water skiing, skin diving, boating, marinas, shoreline activities, and aesthetic enjoyment, but not fishing. Of all beneficial uses of water, perhaps the least progress has been made in recreational use, so far as establishing rights and water quality standards. Water quality criteria for recreational uses have been limited and either very general and qualitative in nature, or quantitative, based on arbitrary assumptions. The plight of water recreation was summed up concisely in a recent National Technical Advisory Committee Report (4) as follows:

> Recreation uses of water in the United States have historically occupied an inferior position in practice and law relative to other uses.
>
> Where maintenance of recreation quality water placed no significant burden on other water users, recreation has customarily been considered an appropriate use. If other uses degraded quality below recreation quality, the recreation user has usually been expected to seek alternative waters, a task constantly rendered more difficult by rapidly expanding urbanization, and industrialization.
>
> In a number of western states, recreation does not appear in the roster of "beneficial uses" enumerated by statute. The recognition of recreation as a benefit and a purpose of water resource development is a matter of recent history for such federal agencies as the Corps of Engineers, the Bureau of Reclamation and the Soil Conservation Service.
>
> The reasons for these priorities in the uses of water are found in the transition from an agrarian to an industrial and urban society. Now the nation faces a new order of social problems including, for the first time in history, a serious concern for the creative uses of the increasing amounts of leisure available to our people. Today there is a growing realization that recreation is a full partner in water use; one that, with associate services, represents a multi-million dollar industry with substantial

prospects for future growth as well as an important source of psychic and physical relaxation.

The NTAC Report (4) concluded that there was an urgent need for systematic surveillance (traditional sanitary surveys broadened to include aesthetic qualities) of waters and waste sources to make effective use of criteria in practice. It also noted that the management of water for aesthetic purposes must be planned and executed in the context of land use, shoreline, and the water surface. Tables 34 and 35 reflect some recent thinking with respect to water quality criteria for the protection of various uses of recreational waters.

Effects of potential pollutants in irrigation return flows on recreational and aesthetic use

Due to a paucity of quantitative data on water quality criteria for the protection of recreational ues of water, the following discussion of the effects of potential pollutants in irrigation return flows is mainly qualitative in nature. It should be acknowledged, however, that the setting of limits on parameters describing minimum desirable water quality for recreational uses is difficult because of variations in may of these parameters, due soley to natural causes.

Potential Pollutants	Adverse Effects
Total dissolved solids Hardness Chloride Sulfate Sodium Alkalinity	None
Nitrate Phospate Tastes and odors	Nutrients for the stimulation of excessive aquatic plant growths and resulting tastes and odors. Adversely affect practically all recreational uses.
Turbidity Color	Characteristic of many return flows. Potentially serious adverse effect on body contact activities and aesthetic appeal.

Table 34. Tentative guides for evaluating recreational waters (61).

Determination	Water-Contact		Boating and Aesthetic	
	Noticeable Threshold	Limiting Threshold	Noticeable Threshold	Limiting Threshold
Coliforms, MPN/100 ml	1000[1]	[2]	-	-
Visible solids of sewage origin	none	none	none	none
ABS (detergent), mg/l	1[1]	2	1[1]	5
Suspended solids, mg/l	20[1]	100	20[1]	100
Flotable oil and grease, mg/l	0[1]	5	0	10
Emulsified oil and grease, mg/l	10[1]	20	20[1]	50
Turbidity, silica scale units	10[1]	50	20[1]	[3]
Color, std. cobalt scale units	15[1]	100	15[1]	100
Threshold odor number	32[1]	256	32[1]	256
Range of pH	6.5-9.0	6.0-10.0	6.5-9.0	6.0-10.0
Temperature, maximum °C	30	50	30	50
Transparency, Secchi Disk, ft	-	-	20	[3]

[1] Value not to be exceeded in more than 20 percent of 20 consecutive samples, nor in any three consecutive samples.

[2] No limiting concentration can be specified on basis of epidemiological evidence, provided no fecal pollution is evident.

[3] No concentration likely to be found in surface waters would impede use.

Note: Noticeable threshold represents level at which people begin to notice and perhaps to complain. Limiting threshold is level at which concentrations prohibit or seriously impair use of water for recreation.

Coliform organisms	Assuming no unusual hazards, a die-away pattern should exist for any such organisms in the irrigation water due to the unfavorable conditions for their existence. Apparently no general evaluation can be made, but conceivably a recreational health hazard could be related to return flows in certain situations.
Pesticides	Suggested limits (4) for most pesticides in municipal supplies are very low. It appears impractical to impose the same limits for recreational use because the water is not consumed by man. There can be both a direct and indirect adverse effect on aquatic life, hence, the standards when established should give primary consideration to tolerances of the aquatic life.

Table 35. Summary of national technical advisory committee report on water quality criteria for recreation and aesthetics (4).

Use	Criteria
Primary Contact Recreation wading swimming water skiing skin diving	log mean of fecal coliforms less than 200 per 100 ml nor more than 10 percent of samples exceed 400 per 100 ml pH range 6.5-8.3 (except from natural causes) Secchi disc visible at minimum depth of effect Maximum water temperature 30 °C (85°F) (except by natural causes)
Designated Recreation Secondary Contact boating marinas shoreline activities	log mean of fecal coliforms less than 1,000 per 100 ml and fecal coliforms should not exceed 2,000 per 100 ml in more than 10 percent of samples
General Recreation Secondary Contact boating marinas shoreline activities	Average fecal coliforms less than 2,000 per 100 ml Maximum fecal coliforms 4,000 per 100 ml
Aesthetics	Freedom from: All Qualitative Assessments: odor, color, turbidity, settleables, floatables, excessive aquatic plant nutrients, excessive temperature

MAXIMUM USE AND QUALITY MANAGEMENT OF IRRIGATION WATER

Maximum Use of Water for Irrigation

Maximum use of available water results when the outflow is at the highest possible salinity level without affecting crop production. The return flow from an irrigated area usually is a combination of drainage water from both tile and open drains, often mixed with waste water from the canal system and runoff from irrigated fields, together with the natural subsurface influents to the river system. So it is difficult to place a specific value on the salinity level of the surface outflow that might be tolerated. Effluent from drainage systems is sometimes of a quality that cannot be used without dilution. Pillsbury (21) reports that the average concentration of salts in tile effluent, in a four-year study in California, was 5,000 mg/l, (EC = 7.4 mmhos/cm at 25° C). Generally, after tile drainage systems are installed, there is with time a gradual decrease in the salinity of the water due to leaching of the salts stored in the soil before irrigation and drainage began. Pillsbury found this reduction could be approximated by the equation

$$EC = 11.74\ y^{-0.30} \quad \text{(Correlation coef. } r = 0.57\text{)}$$

where y was times in years after installation of the tile system. This equation indicates that the average concentration for y = 1 year was about 11.74, and after 10 years was 5.90 mmhos/cm.

These values might be compared with average values of the return flow from the Imperial Irrigation District (25) which averaged 4.3 mmhos/cm in 1966. Improvements in the management of irrigation systems to minimize operational wastes, and maximize application efficiency of irrigation, will tend to increase the salinity of return flows, but should have little effect on the resulting quality of the stream flow. It would be of importance only in downstream areas where dilution and re-use are not possible.

In discussing water quality, Pillsbury and Blaney (9), consider that water having a conductance of EC = 7.5 mmhos/cm is "essentially valueless for irrigation." They point out, however, that under some conditions water of higher salinity can be, and is being, used. An example was the former use of groundwater in the Wellton-Mohawk area in Arizona, where Wilcox and Christiansen (unpublished) found that the water from some of the wells being used for irrigation had a salt content of more than 10,000 mg/l. The use of such water was possible because the groundwater level was far below the root zone, the soils were highly permeable, a copious amount of water -- possibly in the range of two to four times the evapotranspiration -- was used for each irrigation, and salt-tolerant crops were grown. Saturation extracts from soil samples collected had lower salt concentrations than the irrigation water applied. This sample indicates that under some conditions fairly saline waters have value for irrigation, and where return flows can be diluted to reasonable salinity levels, the resultant flow is of value.

Bernstein (21) reasons that drainage water which passes through the root zone under a system of maximum efficiency is of little or no value even if diluted. He stated:

> Drainage water, in the sense in which I shall use the term, refers to the soil solution that has moved below the root zone. Under conditions of maximum efficiency of water use, the drainage water in passing through the root zone will have had its salt content increased by evapotranspiration to the maximum level possible without unacceptable damage to the crop. Such drainage water is spent and can contribute nothing more to the water needs of crops of the same or lower salt tolerance than the crop that it already nourished. This is true even if the drainage water is diluted for re-use with less saline water, for the concentration of salt in the drainage water cannot be further increased without damage to the crop. Therefore, if the water is mixed and re-used, the salt originally present in the drainage water will reappear in the same volume of drainage water that it was contained in after the first passage through the root zone. Indeed, admixture of such maximally used drainage waters with other irrigation water for re-use imposes burdens on the water user, with no benefits. The user will have to apply the extra volume of mixed drainage and fresh water represented by the volume increment of re-used drainage water in the mixture in order to get the same volume of usable water that he would have had if drainage water had not been mixed with the irrigation water. And the drainage system will be burdened by the extra volume of drainage water that it will have to carry.

> The situation changes, however, if the drainage water can be re-used on crops appreciably more salt-tolerant than the initially irrigated crop(s). Thus, if water with an electrical conductivity (EC) of 1 mmho/cm has been maximally used for irrigation of fruit crops whose tolerance is 4 mmhos/cm, the water will have undergone a four-fold concentration as 75 percent of the water was evapotranspired. (We neglect, at this time, salt precipitation and solution in the soil, and salt absorption by the crop.) If the drainage water from the fruit-crop area is available for irrigation of cotton, then 75 percent of the drainage water can be used by the cotton crop as the EC is increased further to the 16 mmhos/cm tolerance level of the cotton. Thus, for any succession of crops, the fraction of maximally used drainage water available for re-use is:
>
> $$1 - EC_a/EC_b$$
>
> where EC values refer to allowable salinities for the first crop, a, and the second crop, b. Maximum allowable salinities that permit essentially full yields (an estimated 90 percent, or more, of maximum obtainable yields) range from two to 18 mmhos.

This theoretical argument assumes that water of any quality can be maximally used to obtain an effluent of such a concentration that it has no further use for the same or less tolerant crops, and that the leaching requirement formula (13), is valid for all water.

In practice, water of relatively low salinity cannot be used in such a way that the effluent has the limiting value. Irrigation application efficiency seldom exceeds 80 percent, and sometimes is less than 50 percent. This means that the quantity of effluent passing the root zone under equilibrium conditions is generally from 20 to 50 percent of the water applied; much more than required for a salt balance. The electrical conductance (EC) of the effluent from a drainage system, except during a period of reclamation of the soil after installation, will seldom exceed five time that of the irrigation water and is often much lower. Thus, waters with an EC above 1 mmho/cm, should have about the same practical value for irrigation as one with a conductance of 0.1 mmho, assuming soil and drainage conditions are satisfactory. Thus, it would be possible to increase the conductance of the water in the main stream from very low values in the headwaters, often less than 0.1 mmho/cm, to a value of about 1 mmho, without decreasing its value for irrigation of most crops.

Further, many low salinity waters have fairly high percentages of Ca and HCO_3. When the Ca ions exceed the HCO_3 ions, on an equivalent basis, these waters are not objectionable, and upon use for irrigation, the salinity of the effluent does not increase in proportion to the amount of evapotranspiration because of the precipitation of lime in the soil. Thus, the formula for leaching requirement is not valid for such waters. For example, Christiansen and Thorne (9-discussion) showed that upon concentrating the water of Logan River, Utah, 300 times, there was an increase in EC of the effluent from its initial value of 0.352 to a value of only 4.12 mmhos/cm, or about 12 times. The leaching requirement formula would imply an increase of 300 times. Considering the solubility of the various salts in the water it was predicted that a concentration of 300 times should have increased the EC to 6.6 mmhos, or an increase of 19 times the initial value.

That an appreciable amount of calcium salts present in the upstream water does not precipitate in the soil as the water is progressively used and re-used downstream, is shown by the early salt balance studies of Scofield on the Rio Grande, as reported by Branson and Lunt (21). He showed that the increase in total salt concentration between Del Norte, Colorado, and Fort Quitman, Texas, was 25-fold (1.27 to 35.4 me/l), while the increase in sodium was 57-fold (0.37 to 21.3 me/l) and in chloride, 131-fold (0.16 to 21.0 me/l). As previously mentioned, Table 4, for the Imperial Irrigation District, shows that the ratio of increase in salinity from inflow to outflow was 1.36 for HCO_3, 2.17 for Ca, 3.5 for total salts, 4.32 for Na+K, and 5.91 for Cl. For some crops and conditions, the increase in the chloride ion may be more limiting when considering re-use than the increase in total salts.

Quality Management

Since irrigation return flow is an integral part of the hydrologic system, it much be dealt with on this basis. In general, it cannot be considered as a separate hydrologic unit, and therefore, methods to control or manage the return flow must be consistent and compatible with the hydraulic system containing the return flow. Salinity is the major problem in irrigation return flow, and the two methods suggested to control it (146) are "dilution (water supply increase) and salt load decrease (desalinization)." Both control measures suggest management factors which might be outside the hydraulic system. While both control measures would be effective, management of the salt load within the hydrologic system should be considered for the required results.

Natural dilution

Dilution of return flow occurs naturally in nearly all upstream irrigated areas. Drainage waters, and other return flows, are usually diluted in the main stream so that the resultant flow is of a quality that can be used downstream for irrigation and other purposes. For example, the water in the Colorado River at Parker Dam, which contains all the return flow from the upper basin of the Colorado River, is still of a quality that can be used for irrigation, domestic and industrial purposes. This water enters the Metropolitan Aqueduct which supplies a considerable portion of the needs of the southern California area. Because of its hardness, however, some of it passes through a water softening plant before entering the domestic distribution systems of Los Angeles and other cities.

Limitations in the effectiveness of dilution. There are both practical and theoretical limitations in the effectiveness of dilution as a means of managing return flows. The practice is necessarily limited to those places where downstream users can make beneficial use of water if diluted to an acceptable salinity level. For example, the highly saline drainage water from the Wellton-Mohawk Project (24) could be used in Mexico when and if diluted to an acceptable salinity level by Colorado River water.

In many upstream areas there is practically no choice; dilution results naturally, and unless the resultant water is of a quality that borders on the unacceptable, little or nothing can be done. In some downstream areas there is no choice; there is no land or other potential use for the return flow, even if it could be physically diluted to an acceptable salinity level. An example is in the Imperial Valley of southern California. The return flow goes to the Salton Sea where the water evaporates and the only use is for recreation. Another example of using return flow, with or without dilution, is the use of water of poor quality in the Grasslands area of San Joaquin Valley for irrigation of pastures and for wildlife. Large areas of waterflow marshes are maintained in California, Utah, and other states, with water of little value for irrigation.

Streamflow regulation for water quality control

Since the early 1900's streamflow regulation by the construction of dams to impound flood flows for subsequent release for power generation and for low-flow augmentation as an aid to navigation has become a well established practice on many rivers and streams throughout the United States. Additionally, the provision of storage capacity for municipal, recreational, and irrigation use in such multi-purpose reservoirs is now commonly included.

With respect to the impact of streamflow regulation on water quality, it was not until sometime later that certain studies (157, 158) illustrated the benefits to pollution abatement from augmentation of low-water flows, although such benefits were incidental to other primary requirements for streamflow regulation.

General water quality considerations related to the storage and release of waters from reservoirs

Impoundments may produce both beneficial and detrimental effects on water quality(118, 159-176). Among the beneficial effects are decreases in coliform bacteria, turbidity, suspended matter, color, biochemical oxygen demand and the leveling out of variations in chemical quality. The potential adverse effects on water quality include a decrease in dissolved oxygen and an increase in carbon dioxide, alkalinity, iron, manganese, and algae. Evaporation losses result in an increased concentration of total dissolved solids. The precipitation of calcium carbonate and silica will partly offset the effect of increasing the salt concentration, and it also accounts for the increase in the proportion of sodium salts. In some instances the salt content of the water being stored is decreased. Bliss (176) reported such a reduction for the Elephant Butte Reservoir. He indicated that some of the apparent loss of salts could be accounted for by the temporary bank storage during the filling period. Water temperature may be increased or decreased, depending on the point of release. This produces variable effects on water quality. Subsequent uses and other factors should be considered.

Legal development of streamflow regulation for water quality control

The concept of streamflow regulation as a specific measure for water quality control emerged only after passage of the first Federal Water Pollution Control Act of 1948. Amendments in 1961 first authorized water quality control regulations as applied to streamflow storage in federally constructed reservoirs. A comprehensive study of low-flow augmentation, including legal aspects, state and national policies, economic factors, technical considerations, and the overall events leading up to its passage in the 1961 act, is well documented by Hull et al (178-183).

Amendments concerning streamflow regulation, which now appear in the act as section 3 (b), are set forth below:

> In the survey or planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other federal agency, consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source.
>
> The need for and the value of storage for this purpose shall be determined by these agencies, with the advice of the Secretary, and his views on these matters shall be set forth in any report or presentation to the Congress proposing authorization or construction of any reservoir including such storage.
>
> The value of such storage shall be taken into account in determining the economic value of the entire project of which it is a part, and costs shall be allocated to the purpose of water quality control in a manner which will insure that all project purposes share equitably in the benefits of multiple-purpose construction.
>
> Costs of water quality control features incorporated in any federal reservoir or other impoundment under the provisions of this act shall be determined and the beneficiaries identified and if the benefits are widespread or national in scope, the costs of such features shall be non-reimbursable.

Problems of interpretation of the 1961 legislation. Immediately after the passage of the 1961 amendments to the Federal Water Pollution Control Act it became apparent that certain workings of the legislation needed amplification, interpretation and quantification before low-flow augmentation as a pollution control measure could be implemented and administered properly. In recognition of the need for better understanding of this newly authorized water quality management tool, a symposium on streamflow regulation for quality control was held in April of 1963, with subsequent publication of the proceedings (184).

Some pertinent comments reflecting the vagueness of the legislation were given by Smith (185):

> The policy decisions posed can be divided into three major categories, each of which involves a number of associated economic and socio-political questions They are: a need to define adequate treatment; a need to develop a basic engineering-economic procedure for appraising the amount of storage required and the value of the storage; and a need to define what constitutes widespread or national benefits. The decision made in each of these areas, regardless of the process followed, represents a value judgment and hence influences the cost-benefit ratio. The available options are many, if not innumerable.

The lack of clear intent of the act was further illustrated by Towne (186) who pointed out that:

> When we try to compare the value of the benefits from using a unit of storage for water quality control with the value of using it to maintain a fishery, or for water supply, or for flood control, or for any of the other uses, we are in difficulty.
>
> If we have to reduce or eliminate some uses because of limited storage capacity or limited runoff, how can we compare the value of a unit of storage for quality control with a unit of storage for some other purpose ? Is flow regulation for water quality control to be placed on a pedestal and considered worth the cost, regardless of the value of competing uses ?

Another facet of the problem was recognized by Vanderhoof (170):

> In some of the 17 western states, use of water for quality control purposes is not recognized as a legitimate use. If storage for regulation of streamflow for the purpose of quality control is included in such a project, it is not now apparent how such water can be reserved for water quality control purposes when prior legitimate water rights are not satisfied.

The regional nature of the conflict between water rights and augmentation of streamflow for water quality control was aptly described by Stein (184):

> Increasing and often conflicting demands of municipalities, industries, and agriculture for water are making eastern water users acutely aware of the lack of certainty of their water rights.
>
> I would expect that in dealing with augmented flows provided through flow regulation for water quality control we will continue to have this uncertainty in the East. I would also expect that with its tradition an accommodation will be reached in the East based on negotiation rather than on legal action. In the 17 western states, however, we are more likely to run into situations that will involve legal actions. It boils down to the fact that there is more water in the East and therefore more room for accommodations. In the West water rights are essential to property rights and are therefore a matter of life and death; every man is fighting for every acre-foot of water he can get.

Present status of streamflow regulation for quality control

The current status of storage and streamflow regulation for water quality control can be best summarized perhaps by noting excerpts of remarks by Morgan (187) in June, 1968:

> ...the subject of "Reservoir Storage for Flow Regulation for Water Quality Control" in reservoir projects of federal agencies has been a topic of extensive re-examination in recent years. These efforts were intensified because of recent criticisms by committees of the Congress regarding inconsistencies of application of reimbursement control. Because these criticisms were directed against Interior's Bureau of Reclamation projects submitted to the Congress for authorization, and because the responsibility of administering Section 3 (b) of the Federal Water Pollution Control Act had been transferred, in the interim, to the Secretary of the Interior, the Department undertook a searching re-examination of past practices and of its own policy stance toward proper application of the provisions of section 3 (b).

> As it now stands, no government-wide policy on water quality control has as yet been formulated, and to date no legislative changes have been recommended to the Congress . . .
>
> In the meantime, the Water Resources Council is continuing and accelerating its efforts to formulate a government-wide policy on the application of the provisions of section 3(b) of the Federal Water Pollution Control Act. It is not possible to predict what that final policy will be.

Morgan noted that since 1961 two major water pollution control laws have been enacted; the Water Quality Act of 1965 and the Clean Water Restoration Act of 1966, in addition to Reorganization Plan No. 2 of 1966, which transferred the primary responsibility for administering the water pollution control act from the Department of Health, Education, and Welfare to the Department of Interior. He concluded that section 3(b) must be interpreted in the light of a new national policy:

> In practice, this will mean a new baseline of water quality, a new definition of what constitutes "adequate treatment at the source" under the provisions of section 3(b), and a new "pre-project" condition against which the additional benefits from quality control storage in any federally-sponsored reservoir must be measured and justified. To go below this baseline of quality would mean that we had substituted federally-financed "dilution" water for adequate treatment at the source -- clearly contrary to the intent of the law . . .

Noting that some states do not recognize water quality control by low-flow augmentation as a legitimate beneficial use, Morgan opined:

> We know this to be the case in a number of states, and we are currently asking ourselves whether or not it makes any sense at all to investigate possibilities of storage for quality control where the legal recognition of its status as a beneficial water use does not exist.
>
> On reflection, we believe it would still be necessary to conduct whatever studies are needed so as to reveal the total effects of the project on all water uses and their quality components. On the other hand, of course, a state with such legal barriers may indicate

> that it wishes to learn what opportunities it thus foregoes -- with a view toward making such legislative and institutional changes as may be needed to avail itself of this added tool of water quality management. A pre-project planning consultation could establish this.

Evaluation of the feasibility of streamflow regulation for water quality control of irrigation return flow

Original consideration and evaluation of the use of streamflow regulation and low-flow augmentation for water quality control was identified with problems of the eastern United States and viewed within the framework of the riparian water rights doctrine. The consideration centered mainly on the release of dilution water for maintaining adequate dissolved oxygen levels in rivers and streams where residual organic loadings were great enough to depress the dissolved oxygen levels below an acceptable minimum or where projections into the future predicted this type of problem would exist.

When later viewed within the framework of the western appropriation water rights doctrine and for use on similar water quality control problems, as well as irrigation return flow (e. g. salinity control), the appearance of basic conflicts with state legislation and difficulty of interpretation of the "substitution for adequate treatment" clause precluded any effective use of the law as originally worded. An exception to such a generalization is the release of stored water on the Colorado River to dilute the flow below the Wellton-Mohawk project in order to keep below 1,500 mg/l the concentration in the water going to Mexico.

In general, low-flow augmentation or streamflow regulation for water quality control in the West would result in a reduction in the amount of water available for irrigation, municipal, industrial, and other upstream uses. Since in many cases established rights to the use of water far exceed the supply, such uses for quality control would also be in conflict with the established water rights. Establishing priority rights for quality control under the existing doctrine of appropriation would be complex.

It appears that a revision of the original 1961 legislation is in the offing. Hopefully this will be more definitive and reflect the changes that have since emerged in national policy toward water quality and pollution control. Until that time streamflow regulation for water quality control of irrigation return flows cannot be relied upon as a useful or important management technique.

Return Flow Control

Return flow control is important primarily in regard to its effect on the quality and pollution vectors of the receiving water. The diversion of water and its subsequent return to the stream without pollution or changes in quality are problems only insofar as they change the ecology of the undiverted water or dry stream bed. On the other hand, methods of control should be sought to prevent undesirable changes in the quality and pollution status of the receiving water. In some hydrologic systems, reduction of the return flow by controlling seepage from canals may be highly important in controlling salinity. However, in some cases and for extreme conditions, it may be necessary to capture, control, and dispose of, or desalinate, the return flow. It is recognized that little can be done in this regard except in the lower areas of the system where it is sometimes possible to bypass, evaporate, desalinate, or otherwise control the return flow.

Canal lining to prevent seepage

Many unlined irrigation canals traverse long distances between the diversion point and the farm land. Seepage losses may be considerable, with resulting low delivery efficiencies. Canal lining has traditionally been employed to prevent seepage and save water, and the economics of lining have been justified primarily on the basis of the value of the water saved. The possibility that water seeping from canals may greatly increase the total contribution of dissolved solids in the receiving waters has only recently been given serious attention.

Canal losses (mostly seepage) may be measured using the inflow-outflow method or the ponding method, or they may be estimated from the following formula (188):

$$S = 0.2C\sqrt{Q/V}$$

where

S = loss in cfs per mile of canal
Q = discharge of canal in cfs
V = mean velocity of flow in fps
C = cubic feet of water lost in 24 hours through each square foot of the canal prism.

Houk (1) reports that the average seasonal canal losses varied from 13 percent of the diversions on the Uncompahgre Project, Colorado, to 48 percent of the diversions on the Carlsbad Project, New Mexico.

If these losses occur mainly on the long diversion lines between the diversion dam and the project and if the soils along the canal alignment are high in residual salts, the salt contribution from this source could easily exceed that leached from the irrigated land to maintain a salt balance. Whether or not the soils along the canal right-of-way are high in residual salts, the salt from this source could be largely eliminated by canal lining. The value of improved water quality is another benefit to be claimed in the economic justification of canal lining.

Bypassing downstream diversions

For areas in the lower part of the basin, bypassing the effluent from drainage systems around downstream diversions and disposing of it directly into the ocean, or back into the stream channel where it will not be objectionable, is probably the most practical procedure. After careful investigation, bypassing proved to be the least expensive and the most practical solution of the San Joaquin Valley drainage problem (21, 124, 189-192).

San Luis or San Joaquin master drain. Several alternatives were considered for removal of the drainage effluent from the San Joaquin Valley. The most promising were bypassing the downstream diversion and discharging the effluent directly into the Suisun Bay, transporting the effluent directly westward to the Pacific Ocean by pipelines and pumping, evaporation of the effluent and storage of the precipitated salts, and desalting and evaporation of the concentrated brine. Investigation revealed that the alternative methods would cost from 1.5 to 8.2 times as much as constructing a 280-mile master drain.

Wellton-Mohawk drainage solution. Another example of bypassing downstream diversions is the solution of the problem in the Wellton-Mohawk district in southern Arizona (24). Irrigation of land along the lower Gila River dates back to 1891 when a headgate structure and a canal 10 miles long were constructed by pioneers. Shortly afterward, a disastrous flood wiped out the canal system and a temporary weir across the river. In 1908 a new river heading was constructed to irrigate 1,200 acres south of the river. By this time, upstream developments made the water supply even less dependable. Farming stopped until 1920 when development of groundwater began. The irrigated area expanded rapidly to a peak of about 11,000 acres during the early 1930's. Then wells began to fail, and groundwater quality deteriorated rapidly due to evapotranspiration and recirculation.

Construction of the Wellton-Mohawk project was authorized in 1947. This project provided for the irrigation of 75,000 acres, including 15,000 acres on a mesa south of the valley. When the irrigation system was planned it was anticipated that drainage facilities would be required, but because the groundwater level was then at a considerable depth it was decided to defer construction of a drainage system until needed. A network of observation wells was installed to observe the rise of the water table. The rate of rise of the groundwater was much faster than had been anticipated. By 1958, the drainage problem had become serious, and investigations were started to determine the most economical solution. The solution adopted was to construct a concrete lined drainage channel through the district, 73 miles long, and to control the water table by pumping from wells. This channel was completed in July, 1961, by which time 62 drainage wells were completed and were being pumped. An additional five wells were soon added, for a total of 67 wells. In 1962, 26,000 acres in the lower part of the area had a water table less than eight feet from the surface. By 1964, this area had been reduced to 7,250 acres.

The salinity of the groundwater was very high. In the beginning, the average salinity of the pumped water was 6,500 mg/l, and it reached a high of 17,000 mg/l. The discharge of this highly saline water back into the Gila River, above its confluence with the Colorado River and Mexican diversions, caused an immediate salinity problem for Mexico. A solution to this problem was worked out with Mexico in 1965, and after a "crash program" of construction, a bypass channel was completed in November, 1965. This solution makes it possible to divert the water to the Colorado River, or bypass it around Morelos Dam, at Mexico's request. On this project, it is difficult to assess what costs should be attributed to the pollution control phases, inasmuch as more than 12 construction projects were involved and the overall project was built in stages.

Evaporation

Evaporation is a natural way to dispose of unwanted waters, but for many locations the area required to evaporate the quantities of return flow involved would make the method impractical. For the San Joaquin Valley problem(26), for instance:

> Nearly 70,000 acres would be required for total evaporation of the waste waters from the Tulare Lake Basin. Though selected sites contain some of the most impermeable soils in the valley, it is technically possible to reclaim them for agricultural purposes...
>
> The infiltration studies revealed rates of downward water movement from a low of 0.0001 to a high of 0.01 foot per day in the selected areas. Based on

> these results, infiltration rates over large areas of the proposed sites were estimated to be from 0.001 to 0.002 foot per day.

Considering that evaporation rates during the summer months might be in the range of 0.02 to 0.04 feet per day, it is clearly evident that when the water becomes concentrated about 20-fold by evaporation, an equilibrium would be reached and as much salt would then be passing downward into the groundwater basin as would be coming into the evaporating area. To reduce this seepage of concentrated brine, it was proposed that:

> The evaporation system would consist of a series of ponds, located at strategic places, such that the progressively concentrated waters would be gradually moved toward the safest areas for final evaporation. Some of the ponds containing the most concentrated brines might require lining.

Preventing seepage of the concentrated brines from returning to the stream channel or to the underground water body would generally be a major problem. Also, in many instances much of the return flow from irrigated areas reaches the stream channels by natural means, and not through man-made drainage channels. Except where salts in the return flow were concentrated to approximately the upper permissible limits by careful soil water management, the loss of all the return flow by evaporation would be objectionable. Where dilution to safe limits is possible, return flow has value to downstream users.

The area required for evaporation could be estimated by assuming that annual rates from the large areas involved would be in the range of 0.6 to 0.8 times the annual evaporation from class "A" pans. Where pan evaporation data are lacking, estimates could be made using reliable formulas. The depth evaporated would probably be in the range of 40 to 100 inches per year.

Mineralized springs

Although evaporation of return flow might be impractical in most cases, it could be useful where water from highly mineralized natural springs that normally flow into streams are diverted for irrigation or other purposes. For example, Milligan, et al (193) found that the LaVerkin Springs in southern Utah produced about 100,000 tons of salt per year in a flow of about 12 cubic feet per second. The Bureau of Reclamation studied the effect of this salt addition on the resultant quality of the water and found that, after the development of the Dixie

Project in southern Utah, the effect of removing the flow and salt of LaVerkin Springs would be to reduce the weighted mean annual salt content of the Virgin River at Littlefield, Arizona, from an estimated 2,370 mg/l to 1,790 mg/l, or about 600 mg/l. During June and July, the reduction would range from 800 to 1,000 mg/l.

> The physical accomplishment of the collection and removal of LaVerkin Springs water would not be simple. The springs emerge in a narrow steep canyon..... Any removal scheme would likely involve pumping the mineral water out of the river channel during low flow periods. It might be possible to convey the water to the Bench Lake area and there provide evaporation opportunity (193).

Another example in Utah (193) would be the possibility of diverting the highly mineralized water from Crystal Springs, which enters Bear River above the Federal Migratory Game Bird Refuge at the northeast end of Great Salt Lake. The flow of about 3.5 cf/s with more than 400 tons of salt per day, could either be evaporated, conveyed in a separate channel to the Great Salt Lake, or temporarily stored during the low flow periods and discharged back into the river during high flow periods. The storage requirements for this third alternative would be about 5,000 acre feet. No estimates have been made of the cost or benefits of these alternatives. However, if it is possible to control or eliminate natural mineral springs as a source of salt, the water in the system would certainly be improved for irrigation and other uses.

Control of leaching

Another approach is to control the application of water to land in order to minimize salt pickup in geologic formations. The most drastic action is to eliminate irrigation in areas of high salinity such as those where the soils are formed from salty shales. Preventing or reducing the amount of water penetrating to deeper soil stratas high in salt would also effectively reduce the salt load in the return flow. The use of artificial or natural barriers below the root zone, coupled with drainage systems to interupt water applied by irrigation before it reaches the deeper stratas, would be effective. Regulating the amount of water applied to the land and thereby regulating the amount of drainage water represents a combination of controlled leaching and dilution

Desalinization and Contaminant Removal

The three major categories of contaminants relevant to irrigation return flow quality are minerals, nutrients, and some pesticides (123). While removal of these three contaminant categories is technically feasible (194), the technologies are young and only recently have advanced beyond the pilot plant stage for some processes and are still in the research and development stages for others. The two major classifications of technology relevant to the above contaminant categories are desalting and advanced waste treatment. The desalting technologies are oriented toward removal of "minerals," though desalting processes will remove most contaminants. The advanced waste treatment technologies are oriented largely toward removal of nutrients and other contaminants common to municipal and industrial waste effluents. There has been but limited formal inquiry into the subject of treatment of irrigation return flows. The results of two case studies are presented to provide some insight into the cost of applying advanced waste treatment and desalting technologies to irrigation return flows.

Treatment for pollution control in San Joaquin Valley

In the San Joaquin Master Drain study, pollution abatement was the motivation for considering drainage water treatment.

Howe(195) has pointed out that desalting technology could well be applied to irrigation return flows, with electrodialysis probably the most suitable process. Applying this technology to the San Joaquin Valley drainage problem, desalted drainage water could probably be produced at about $117 per acre-foot. This plan was amplified by Baker (196). The 195,000-acre-foot per year of salvaged water would have value for municipal and industrial use, leaving only 33,000-acre-foot per year of brine to be disposed of by transport to the sea. The California Department of Water Resources concluded that treatment of San Joaquin Valley agricultural waste water for consumptive re-use was not economically sound (123, 124). Although this plan was not economically feasible it was one of the first formal investigations for desalting irrigation return flows.

This same study stimulated further formal investigation of treatment of irrigation water. An alternative plan was to transport this water to the San Francisco Bay delta, but it was found that this would result in unacceptable nitrate levels in the receiving water. The concentrations of salts, phosphates, and pesticides were felt to be insignificant problems to this receiving water (197). This led to the recommendation that studies be pursued to establish the economic feasibility of nitrogen removal of the San Joaquin Valley drainage water. Such a pilot plant study site has since been established at the Interagency Agricultural Waste Water Treatment Center near Firebaugh.

Studies are being conducted to find the best method for removal of nitrate from the waste water before it is discharged into San Francisco Bay. Methods being considered include denitrification (reduction of nitrate), "algae stripping" (the growing and harvesting of algae), and the removal of nitrate by selective exchange resins (123). Cost estimates indicate it would be cheaper to remove the nitrate from the water and discharge the water into the bay than it would be to leave it untreated and transport waste water into the ocean.

Treatment for water supply

Irrigation water supply augmentation was the primary motivation of Maletic, Sachs, and Krous (198) in their study to evaluate the economic feasibility of desalting drainage water, using a 10,000-acre area near Yuma, Arizona, as a case study. Benefit/cost ratios, using desalted drainage water as a supply for irrigation, ranged from 0.86 to 1.62. The most favorable B/C ratio resulted from utilizing the multistage flash process and nuclear energy. Cost of energy was set at 3.13 mills/kw hr. The calculation was based upon a feed water salt concentration of 5,330 mg/l, and a 50 mgd nuclear dual purpose plant. Cost of this water was calculated at \$109/acre-ft (34¢/1,000 gal) using a cost formula developed by the Oakridge National Laboratory. Benefits were fewer than costs for all salinity levels of product water when the energy cost was 6.0 mills/kw hr.

A further study (199) considers irrigated areas in Arizona and California to examine benefits and costs associated with using desalted water for irrigation. Value of desalted water for irrigation has been considered also by Vilentchuk (200) and by Hammond (201).

It should be emphasized that desalting merely divides the stream into two streams, a large one of desalted water, and a smaller one of brine. This brine must then be disposed of by transportation to the sea or other point of disposal, or it must be evaporated. For some locations, the cost of either method would be prohibitively high (123).

Pesticide removal

There appears to be no concerted effort directed at developing a technology aimed specifically at pesticide removal. Pesticides are felt to be no problem for the San Joaquin Master Drain case (197). Activated carbon columns have been used to concentrate pesticides, however, and could provide the basis for treatment, should pesticides become a problem.

Nutrient removal technology

"Advanced waste treatment" is the term used by a research program of that name (194) currently housed in the Federal Water Pollution Control Administration, to study treatment methods for removal of water contaminants not normally removed sufficiently by the usual water or waste treatment processes. The program had its beginning in 1960. As applied to waste water, these advanced waste treatment methods often are called collectively "tertiary treatment." Pollution control or water supply augmentation through re-use are the primary incentives for application of advanced waste treatment methods. The particular method chosen depends upon the constituent(s) which require removal, as some of the methods are specific to particular water constituents.

The water contaminants for which removal processes have been and are being investigated include turbidity, hardness, phosphates, nitrates, ammonia, and minerals (194). Among the processes investigated (202) are microstraining (turbidity), diotomaceons earth, (turbidity), granular activated carbon, powdered activated carbon (soluble organics), chemical clarification (turbidity, phosphates, hardness), biological nitrification-denitrification (nitrates), air stripping (ammonia), and desalting (minerals). Costs of treatment range from 1.5¢/1,000 gal for microstraining to 15¢/1,000 gal for chemical precipitation -- based upon projections from pilot plant operation for plants of the 10 mgd size; the desalting cost projections include 16¢/1,000 gal exclusive of pre-treatment and brine disposal for electrodialysis, and 48¢/1,000 gal for freezing. More detailed cost figures and the assumptions used are given by Smith (203). Research on these various processes is continuing, while pilot plant experience is being gained at such centers as Lebanon, Ohio and Pomona, California and other locations operating single pilot plants.

A further listing of removal processes for nitrogen and phosphorus is given in Table 36 by Eliassen and Tchobanoglous (204), with their cost figures.

The cost data in Table 36 give an order of magnitude estimates, since full scale operating plants do not exist for several of the processes listed. In addition, costs are dependent upon physical and economic circumstances unique to a particular site. It is clear also from the data that many of the processes listed are not specific to either nitrogen or phosphorus removal (for example, electrodialysis is an expensive method of removing nitrates, if nitrate is the sole concern.)

Table 36. Processes used for the removal of nitrogen and phosphorus (204).

Substance removed	Removal process	Cost ¢/1,000 gal
Nitrogen	Anaerobic denitrification	2.5- 3
	Algae harvesting	2-3.5
	Ammonia stripping	.9-2.5
	Ion exchange	17- 30
	Electrochemical treatment	.4- .8 (energy only)
	Electrodialysis	10- 25
	Reverse osmosis	6.5-9.3
	Distillation	40-100
	Land application	
Phosphorus	Chemical precipitation	1- 7
	Sorption (activated alumina)	4- 7
	Ion exchange	17- 30
	Electrochemical treatment	.4- .8
	Electrodialysis	10- 25
	Reverse osmosis	25- 40
	Distillation	40-100
	Land application	7.5- 15

One well known plant (which began operation in 1965) having data available for the chemical precipitation process and the activated carbon sorption process is located at South Lake Tahoe. Of interest here is the phosphate content, which is reduced from 25-30 mg/l to 0.1-1.0 mg/l in the chemical precipitation process; the carbon column reduces total organic carbon from 30-60 mg/l (205). Total costs (fixed costs and operating costs) are estimated at 14¢/1,000 gal for phosphate removals by chemical precipitation and the final polishing for other residuals with activated carbon, for this 2.5 mgd plant. In another study on this plant, Culp and Slechta (206) found that carbon treatment costs 6.5¢/1,000 gal which includes both fixed and operating costs; the latter includes carbon regeneration.

Phosphate removal processes and costs are summarized in more detail in a feature article in Environmental Science and Technology (207), which also summarizes data from eight pilot or newly operational full scale plants employing a phosphate removal process. Costs reported range from one to 10¢/1,000 gal with removal efficiencies mostly 90 to 95 percent. Probably most of the feasible processes for removal of nitrates and phosphates have been explored, and the most promising processes have been developed further on a pilot plant scale. The major advances in technology will probably come from improving design and operating characteristics of these pilot and full scale plants and in lowering costs of recycling chemicals. With a strong emphasis on reducing nutrient levels in receiving waters, nitrate and phosphate removal will surely be practiced on a much broader scale. Costs of nitrate and phosphate removal presumably will be reduced because of this increased practice; however, the amount of reduction and the lower limits of costs are not implicit in the literature.

The advanced waste treatment technology gained through application to municipal and industrial treatment can provide a basis for projecting feasibility and cost for treating irrigation return flows. The Firebaugh study is of great value in delineating the technology and economics specific to irrigation return flows. The diffuse nature of irrigation return flow is an aspect of the problem that is relevant to treatment feasibility. Thus the extent to which return flows, for any given irrigated area, are amenable to collection, and the cost of such collection, should be evaluated prior to entertaining the concept of treatment on a broad scale.

Removal of minerals

In Table 37 most of the basic desalting processes and the installed capacity, through 1967, are indicated by type of plant. Technology is probably most advanced for the multistage flash process (MSF). The

Table 37. Distribution of desalting plants by type of process (213).

Process	Number of Plants	Plant Capacity MGD	Percent Total
Total all processes	627	222.3	100.0
Distillation	585	216.6	97.4
Multistage flash (MSF-D)	137	153.3	
Submerged tube (ST-D)	293	37.5	
Long tube vertical (VTE-D)	92	16.6	
Flash (F-D)	46	7.1	
Vapor compression (VC-D)	17	2.1	
Membrane	38	5.1	2.3
Electrodialysis (E-M)	36	5.0	
Reverse osmosis (R-M)	2	0.1	
Crystallization	4	0.6	0.3
Secondary refrigerant (SRF-A)	1	0.2	
Vacuum freezing Vapor compression (FV-A)	3	0.4	

reverse osmosis process is classed as a "breakthrough" in technology, with the development of high flux membranes in 1960 (208) and has generated considerable enthusiasm because of its low energy requirement. A major technical problem involves membrane support to withstand the high pressures against the membrane; the solution must be sufficiently economical that high capital costs do not nullify the low energy requirements. The various processes listed in Table 37 are described well in the booklet, A-B-Seas of Desalting (209).

Energy requirements. The reversible work required to remove pure water from sea water is 2.8 kw hr/kgal at 25°C. The degree to which the particular equipment or process follows a reversible path is a measure of its "effectiveness of energy utilization." As a rule, achieving higher thermodynamic efficiencies requires more capital and maintenance expenditures, so there exists a practical limit as to how far the ideal can be pursued.

Figure 7 illustrates the comparative energy requirements for the various major processes. It is immediately apparent why reverse osmosis is so attractive, with an energy requirement of only 26 kw/hr/kgal, as compared with about 290 kw hr/kgal for multistage flash distillation (210). It is also apparent that an operating plant's energy requirements far exceed the theoretical limit of 2.8 kw hr/kgal. The practical minimum is about four times the theoretical minimum, according to Murphy (211).

Sources of energy. The source of energy bears on the problem only as related to cost. Depending upon the situation, any one of several fuels may be the most economical. Nuclear energy is easily available to any remote location, while the economy of coal, oil, or gas depends more on the degree of logistic support. The cost of nuclear power is decreasing as technology advances; also cost of energy declines as the plant scale increases. Plants in design of 500 to 1,000 MW size have projected costs of 3.5 to 5 mills/kwh, compared to plants in operation in 1965 producing power at 5 to 10 mills/kwh (212).

Dual plants. The dual purpose plant, which will produce both electricity and desalted water, is strongly advocated (210). The water production for such a plant bears only the incremental costs. Figure 7 shows that the energy utilized decreases from 290 kwh/kgal for a water-only distillation plant to 170 kwh/kgal for a dual plant. It is further suggested by Reichle that the established electric utility companies can produce electricity and steam at the lowest cost. An additional advantage exists in that off-peak energy production could be utilized for desalting. No dual purpose plant has yet been built, but projections (214) indicate that by 1975 to 1978 the nuclear and water

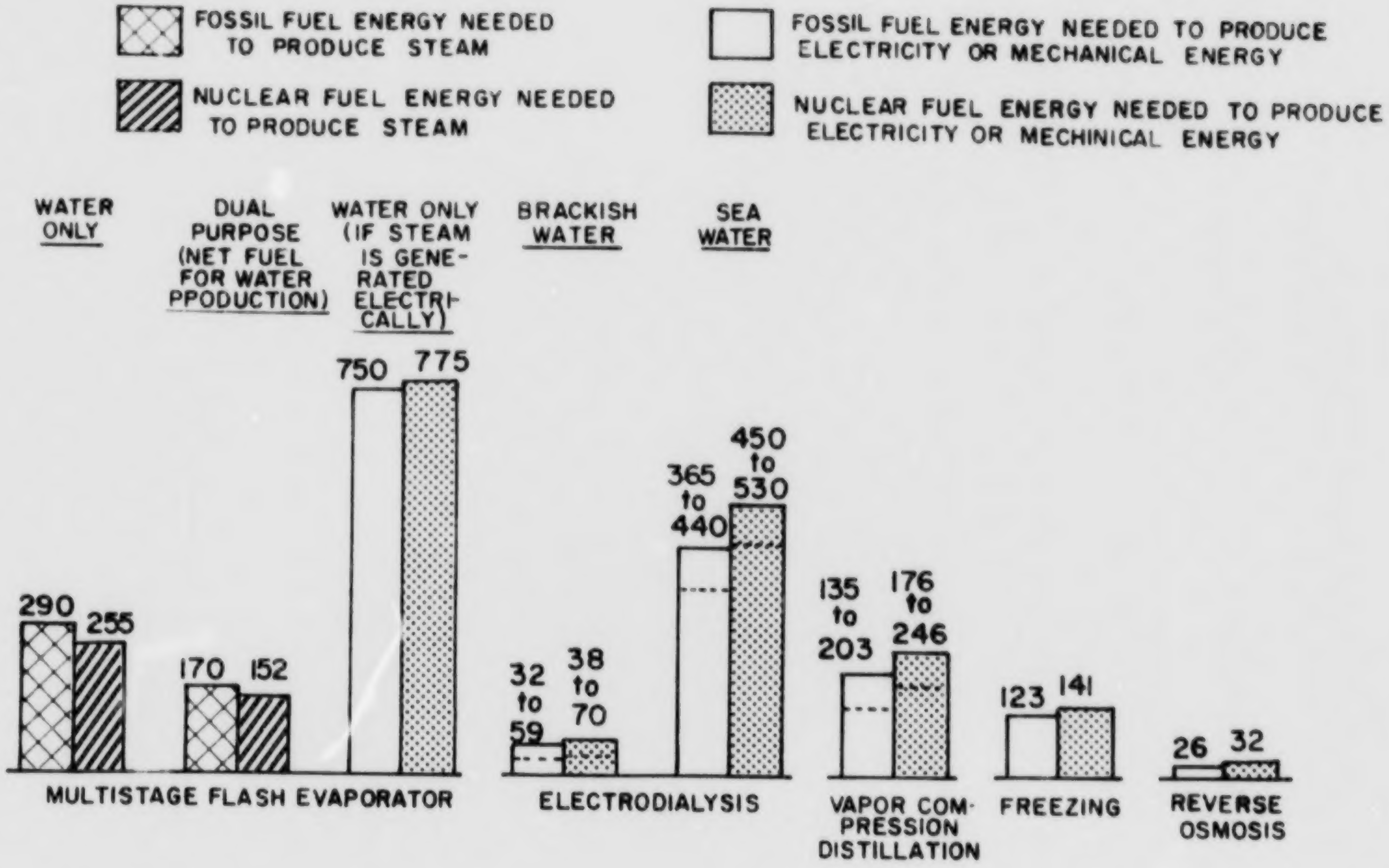


Figure 7. Typical fuel energy required by various desalting processes to produce 1,000 gallons of fresh water (in kilowatt-hours)(210).

technologies will be sufficiently advanced to permit such combinations of the dual purpose plant.

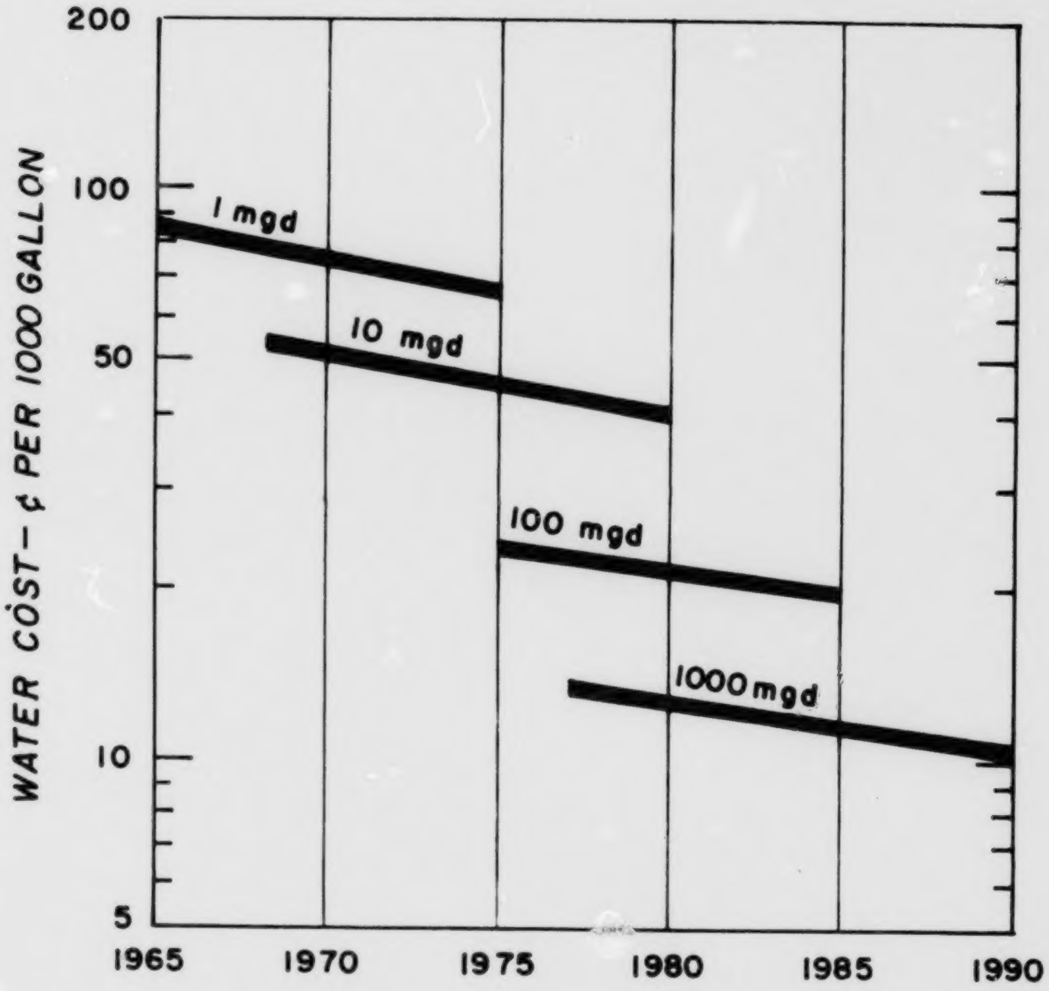
Cost of desalted water

Cost of desalted water is related directly to the gross considerations of process technology and scale of operation; other more detailed operational considerations such as load factor, access to fuel and brine disposal, also bear on the problem. For example, the cost reduction from \$4/kgal to \$1/kgal from 1955 to 1965 was effected through improvement in process technology. The cost effect of scale and advancements in technology can be seen in Figure 8, which is based upon projections by the Office of Saline Water (215). It should be emphasized that the cost projections of Figure 8 are indicative of a probable trend and and that the cost figures probably are in the proper order of magnitude. Additional insight into costs can be seen in Figure 9.

It should be noted also that most of the optimism for this low cost water is based upon development of dual energy-desalting technology. Plans are being revived for the 100 mgd Bolsa Island dual purpose plant of the Metropolitan Water District of Southern California. Cost of water from this plant was anticipated originally at 25¢/1,000 gal; currently costs are anticipated at 32-35¢/1,000 gal.

There is considerable optimism for the reverse osmosis process, because of its low energy requirement. The energy cost for reverse osmosis, using say 30 kwh/kgal energy and 0.5%/kwh energy cost, would be 15¢/kgal. Using the minimum energy projected for an electrodialysis plant of 32 kwh/kgal, seen in Figure 7, gives about the same value, 15¢/kgal. Amortized capital costs and operation and maintenance costs are not included in this rough calculation. The cost of 15¢/1,000 gal for energy gives some idea of the rock bottom price of desalted water by reverse osmosis or electrodialysis.

In developing cost estimates for specific proposed MSF desalting plants, the computer cost models developed by the Oak Ridge National Laboratory (ORNL) should be mentioned. The ORNL program considers many detailed factors, including feed water temperature, cost of materials, load, size, cost of energy and interest rate. The program optimizes plant design and gives fixed and operating costs. The program was used by Maletic, Sachs, and Krous (198) in their feasibility study for desalting irrigation return flows for recycle back into the irrigation system. Desalting for irrigation does not appear to be an economic solution, except under some unusual circumstances where it may be combined with power production, dilution, and treatment of water for domestic or industrial use.



Based on:
1. Distillation technology
2. 6% fixed charge rate
3. U. S. construction and operation
4. Dual purpose plants
5. Most probable energy costs

Figure 8. Projection of sea water desalting costs for a range of plant sizes (215).

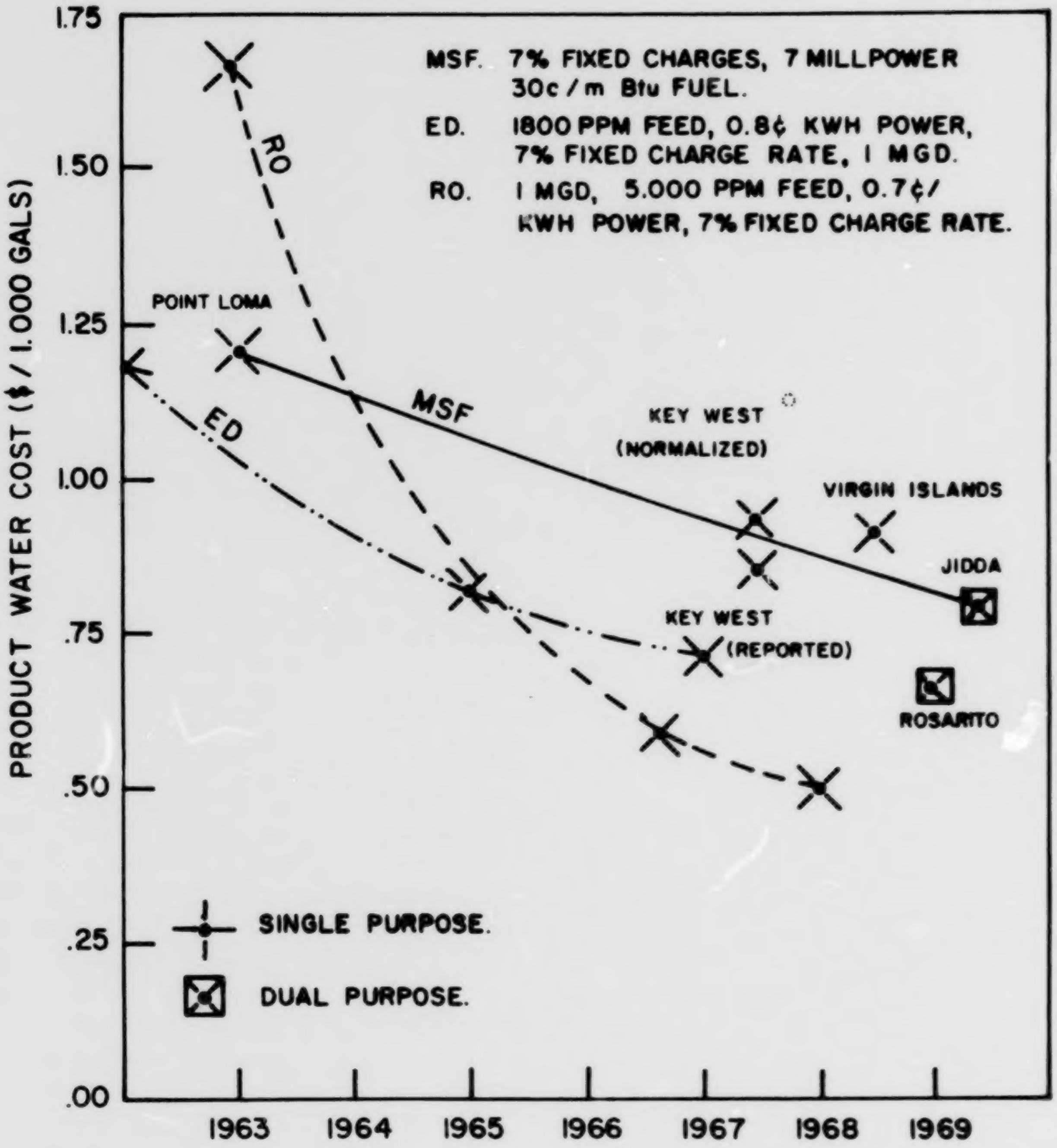


Figure 9. DESALTING PRODUCT WATER COST VS YEAR.

AFTER: OFFICE OF SALINE WATER, " SALINE WATER FIVE YEAR PROGRESS REPORT JANUARY 1963 THROUGH MARCH 1968," APRIL 1968.

Conventional water. Cost of conventional water is relevant to the irrigation return flow problem because of its potential value as a water supply. As costs of incremental development of conventional supplies exceed the costs of desalting, the water supply motivation will assume increasing importance in alleviating the pollution problems of irrigation return flows. This implies that a "systems" approach is warranted in decisions concerning abatement of irrigation return flow problems. Thus, damages due to pollution and benefits from water supply augmentation should be weighed against the alternative cost of transporting drainage water to the sea. Some insight into costs of conventional water supplies is relevant,therefore to the problem of irrigation return flow.

Figure 10 provides an order of magnitude cost estimate of conventional water as affected by transportation, distance, and supply needed. Figure 11 is an envelope curve assessing costs of conventional supplies. An order of magnitude assessment of nominal costs of water for various purposes is seen in Table 38.

Another insight concerning cost of conventional water supplies is reported by Koenig (216), who analyzes costs of storage for more than 1,000 U. S. reservoirs. He converts the cost per acre feet for various sizes of reservoirs to an annual basis, Table 39. Koenig further analyzes conveyance costs, summarized in Table 40.

Koenig illustrates the types of final costs arrived at by his procedures for a hypothetical new conventional supply for Pierre, South Dakota. Figure 12, taken from his work, shows the relationship between water cost, production level, and conveyance distance. The zero conveyance costs consist largely of treatment for both the surface and groundwater cases (softening for both and softening only for the latter), and about 20 percent of the cost for impoundment. Conveyance costs are seen to add the difference between the zero conveyance curves and the 100-mile and 500-mile curves.

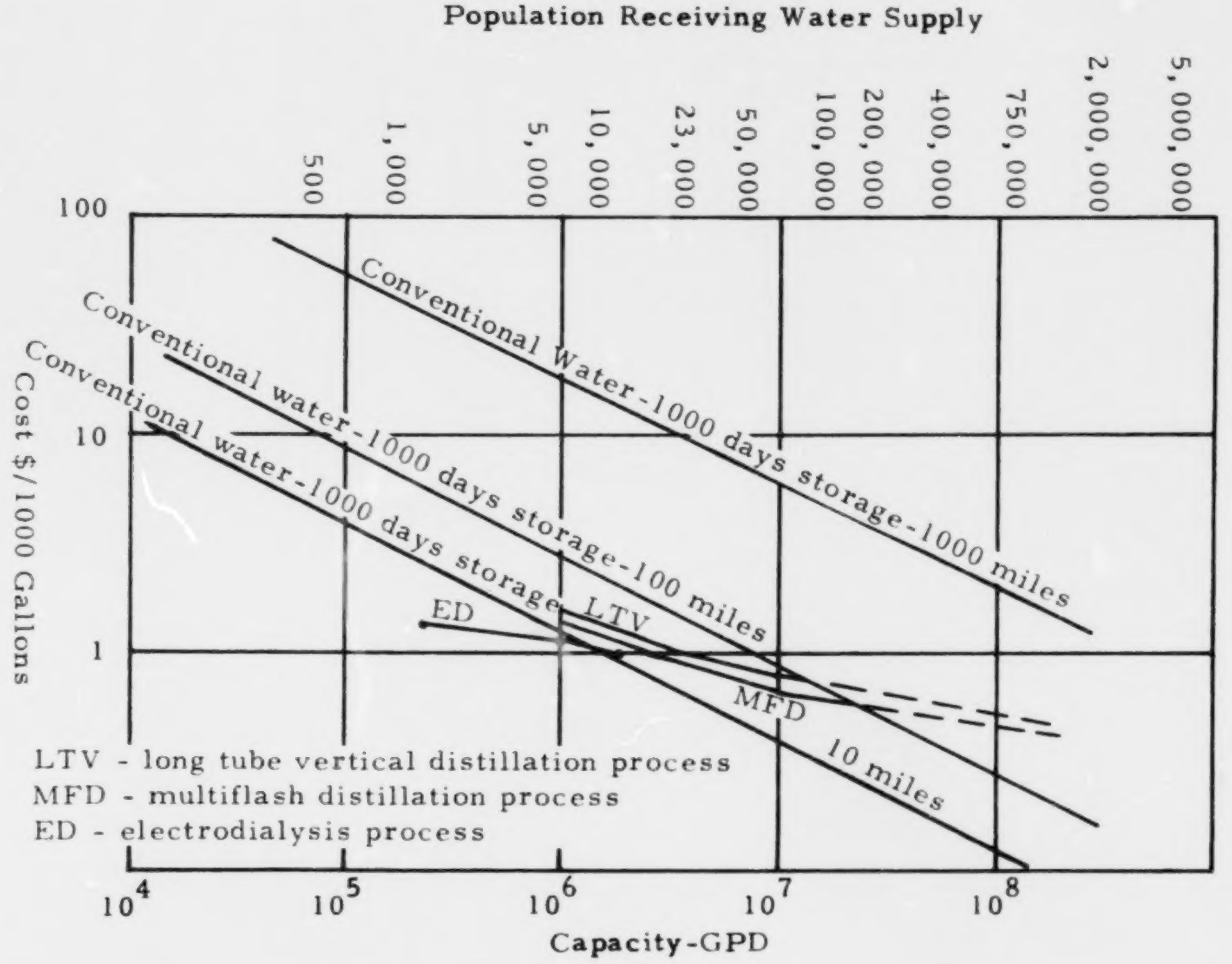


Figure 10. **Cost of conventional water vs. water from desalinization plants** (212).

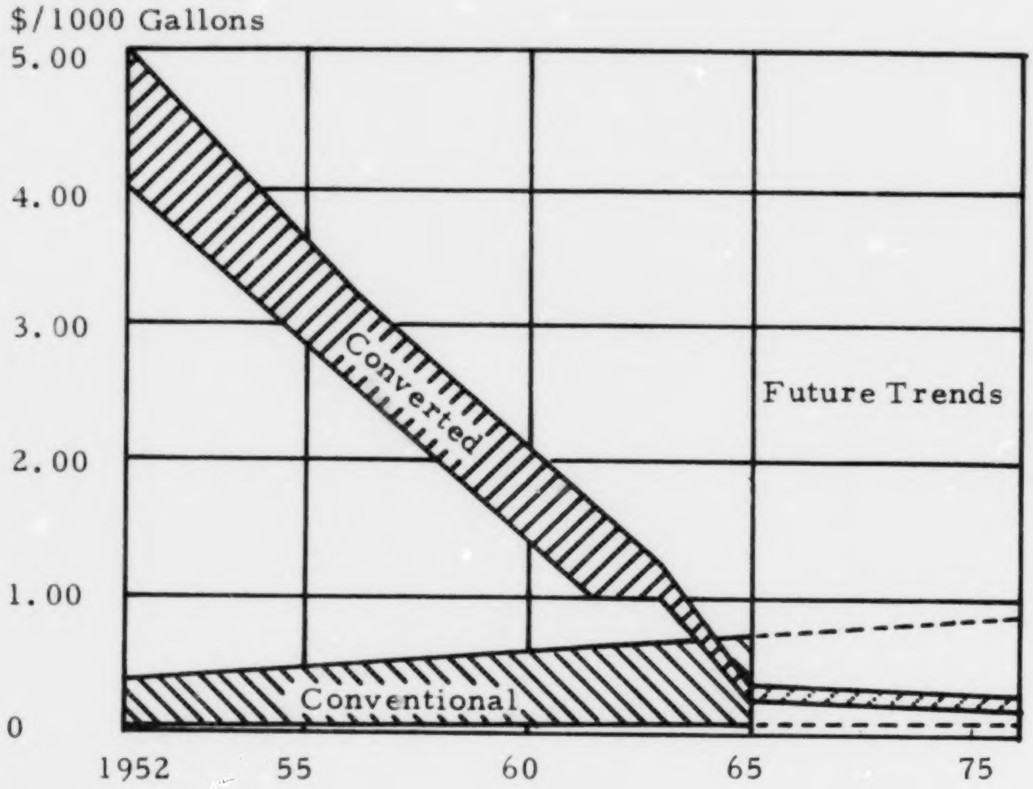


Figure 11. Cost of fresh water--conventional and converted (217).

Table 38. Typical rates for water in western United States (from report by Los Angeles Chamber of Commerce)(218).

Water User	Approx. Water Rates per acre-ft/($/kgal)		
	Low	Average	High
Irrigated agriculture			
Bureau of Reclamation, charges	$1-2 (.003-.006)	$2-6 (.006-.02)	$27 (.08)
Independent districts, charges	$2-5 (.006-.013)	$5-10 (.015-.03)	$40 (.12)
Individual wells, costs	$2 (.006)	$10 (.03)	$20 (.06)
Municipalities			
Cost of water to the city	$2 (.006)	$30 (.09)	$100 (.30)
Owens Aqueduct (L.A.)	-	$19	-
Pasadena, MWD water (1956)	-	$44 (.13)	-
Retail charge to consumers	$5-10 (.015-.03)	$50-100 (.15-.30)	$200 (.60)
Industries, charges, or costs	$2 (.006)	$50-100 (.15-.30)	$1000 (3.00)

Table 39. Illustrative annual costs of impoundment (216).

Capacity (acre ft)	Unit costs (capital recovery and DM) ($/yr/acre ft)
1,000	28.5
10,000	8.9
100,000	3.1
1,000,000	1.3
10,000,000	0.75

Table 40. Costs of water conveyance by pipeline (216).

Conveyance cost, $/kgal/mile	Average Conveyance Rate MGD
0.032	0.1
0.0083	1
0.0031	10
0.0012	100
0.0005	1000

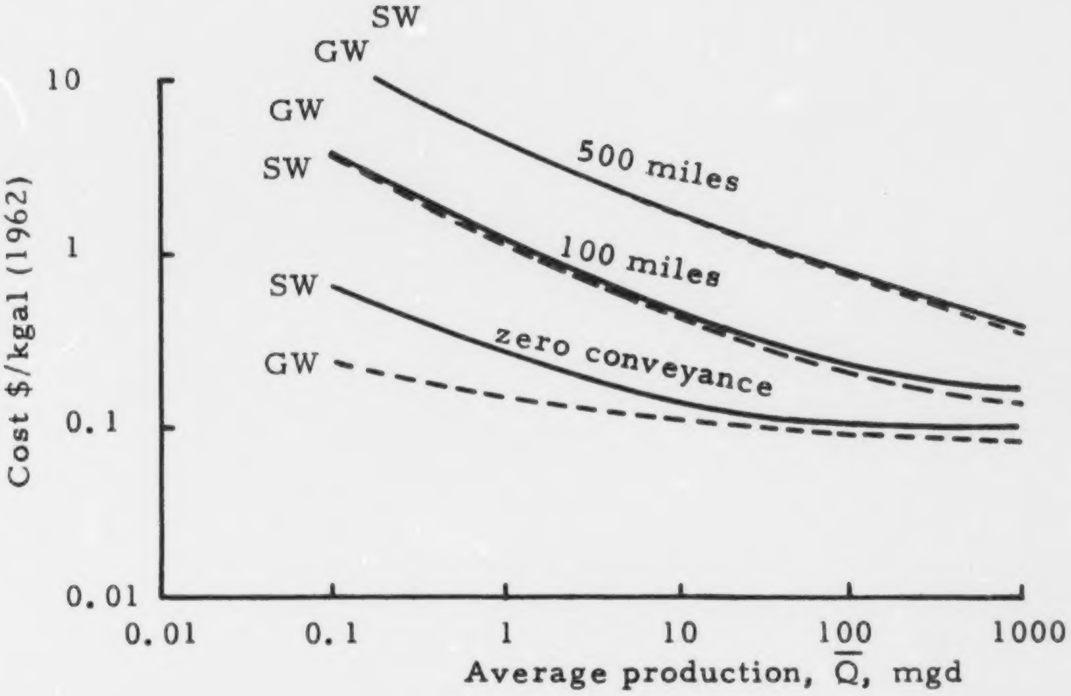


Figure 12. Exemplary costs of conventional supply at Pierre, South Dakota (216).

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ECONOMIC ASPECTS

Economic Considerations

Practically no research has been done on economics of the problem of water quality and irrigation return flows. However, a great deal of empirical and conceptual work has been accomplished which is basic and of value in extension of research to more specific analyses of the problem. Economic aspects of pollutional problems of irrigation return flows include the economic impact of lowered water quality, and economic feasibility of control measures and other adjustments.

The unique and extremely difficult economic problems related to irrigation return flows involve external economies and diseconomies. These problems occur both with water quality and quantity considerations. Both farm and non-farm business enterprises must be concerned, for they are interdependent in the physical use of resources, yet they make decisions independently. These problems frequently are referred to in terms of incidence of costs and incomes.

In irrigation return flows, a portion of the original water supply is re-used for irrigation one or more times, and re-used water is usually of poorer quality than the original supply. The re-use of water has important implications in the total supply and efficiency of use. A given storage supply development may total more water for irrigation than is suggested by the reservoir capacity and project size. This re-use has significant effect on the financial feasibility of the project. This apparently has not been completely recognized in project formulation.

Associated with these return flows and re-use for agriculture or for other purposes is deterioration of water quality, although quality changes cannot be analyzed without associated quantity considerations. Water for re-use, then, has a diminished quality value which could offset its quantity value.

A major hypothesis is that the re-use of water through return flows shifts the cost of water quality deterioration from the upstream to the downstream user. The upstream user applies water and makes decisions without regard to disposal costs of such wastes as irrigation, livestock, pesticides, andherbicides; thus, in terms of economic criteria he seemingly overproduces since his costs are understated. In

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turn, the downstream user is affected by the quality deterioration from upstream; his costs are overstated and production is less than an economical optimum otherwise. To the extent that irrigation return flow influences quality deterioration downstream, the costs of quality deterioration are transferred from one unit or area to another through the technical or physical linkage between the production processes. The market price system does not reflect these conditions nor adjust for these economic inefficiencies and incidences of costs and benefits. Arrangements outside the regular market operations are required to accomplish improved efficiencies and otherwise to alleviate problems associated with water quality deterioration.

Absence of property rights in water quality complicates greatly economic and institutional analyses and solutions to water quality problems. Water rights, compacts, etc., almost universally have been expressed in terms of quantity. Responsibilities and obligations seldom are attached with reference to water quality.[1] Thus, if an upstream irrigator develops and applies water, part of which returns to the stream in lower quality, the downstream user still has his quantity right but the quality may be less than satisfactory. In an economic analysis of such conditions, several questions need be answered, such as:

a. How are costs and damages to be assessed and collected?
b. What are the net diseconomies?
c. What remedial measures are warranted and feasible?

Analytical techniques

A substantial need exists for continued efforts in improving and developing analytical techniques for appraising the economic impact of water quality deterioration in irrigation return flow. Farm and enterprise budgets have long been the basis for estimating benefits from irrigation development. The Bureau of Reclamation has utilized them extensively, as have agricultural economists generally in appraisal of resource development. However, budgeting is cumbersome in terms of the range and number of situations that can be analyzed readily. This technique is not especially useful either in considering alternative major uses of resources, in estimating secondary or side effects, nor in estimating effects on related sectors of the economy.

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[1] There are exceptions. For example, the New Mexico-Colorado Compact on the Rio Grande does have a quality clause and the State Department has imposed a maximum of 1,500 mg/l on Colorado water delivered to Mexico.

A more recently used technique for regional and small-area analyses is the inter-industry input-output (I-O) model. The Colorado Economic Base Study (219) which utilized the inter-industry technique is the most notable analysis to date involving agriculture and other water uses, water quality, and return flow problems. This analysis shows inter-dependence among sectors of an economy. It estimates total economy effects of a change in one or more sectors. It utilizes gross magnitudes, for example, output (income), or employment. It does lack inter-regional analysis usefulness. It does not provide a measure of net benefits. It is expensive, especially in terms of meeting data needs. There may be some problems in the input-output technique if only a small area were involved in the analysis. However, as part of a larger I-O model, appraisals can be made for relatively small areas and adjustments.

Economic projections

Feasibility of control measures, farm income appraisals, management plans, and other aspects of benefit cost analyses usually extend over at least a 50-year period. A major current effort on national and regional projections is sponsored by the Federal Water Resources Council. The Office of Business Economics, U. S. Department of Commerce, has general leadership and is directly responsible for the non-agricultural projections, including population, employment, and income. Economic Research Service, U. S. Department of Agriculture, is responsible for agricultural and forestry projections, the latter in cooperation with the U. S. Forest Service. Projections are included for 167 economic areas covering the United States and for hydrologic sub-regions within each water resource region. Type I studies of the Water Resources Council should be useful for appraisal of the impact of deteriorated quality of irrigation return flows. Additional adaptations are needed however, for these small-area analyses.

Literature is available on interest-rate considerations. A wide difference of opinion is apparent among economists and others as to the appropriate rate or rates. A proposal for a substantial adjustment upward (from 3-1/4 percent to 4-5/8 percent in 1969) is under consideration by the federal government. This rate will be specified for public investments and project features. A different rate should likely be applied for private capital involved, but difference of opinion exists as to whether this rate should differ from the public rate, and if so, what the rate should be.

Agricultural Income Impacts

The irrigation return flow problem basically involves an area approach. But in agriculture, the farm is the major unit and a source of quality change and therefore, is the major point of emphasis.

Production and damage functions

Several state and federal agencies either have completed or have in process fundamental and significant data relating salinity and water quality to crop production rates. This material was used by Pincock and Stewart in the Colorado Economic Base Study (220, 221). The reports contain a large portion of the available material. Pincock found major gaps in available data of the kind needed for farm income analyses. Application of experimental data to actual farm conditions seemed impossible in any direct sense because managerial adjustments on farms removed direct comparison potentials; thus, his estimates of quality impact were necessarily based on informed judgments. Information is needed on production and damage functions (experimentally and in experience), with several crops for various levels of water quality, water quantity, soil quality and climate. There has been much valuable research accomplished on an experimental basis relative to production functions of specific crops under different water and land quality conditions.

Farm incomes

Estimates of farm incomes are needed for relevant levels of water quality under soil, cropping patterns, water use, etc., conditions relevant to the return flow situation at hand. There is need for physical data and price and cost information and projections. Much of this data could be derived from farm enumerative surveys, as a basis of economic analysis of return flows. Information is also needed on the effect that deteriorating quality has on land values. Although decreased land values obviously would have an adverse effect on land owners, especially if they had occasion to sell, yet these lower net incomes could be capitalized into lower values and new land owners might be less adversely affected than appears from an income criterion, assuming that water quality, or soil, or both, did not continue to deteriorate. Projection of water availability, crop requirements, efficiencies, and net disappearance of particular land and water qualities are critical inputs to the income analysis, both at the farm and area levels, and to appraisal of farm adjustments and courses of action.

Profitable farm adjustments

Profitable adjustments to various levels of water quality need to be appraised. Adjustments made by farmers in actual operations needed to be identified and evaluated as part of this total process. These analyses are needed for appraising economic impact on agriculture and other segments of the economy from various changes in quality deterioration. The estimates of income and other effects are basic to feasibility appraisals and to adjustment programs. Estimates are needed of the effect on upstream users who do not incur quality control costs. In turn, there is a need to know the impact of quality deterioration downstream as well as the kind of adjustments these users would make. Such analyses have not been made except in the Colorado Economic Base Study.

Other Impacts

The impact of water quality deterioration associated with return flows can be widespread. We note briefly here both domestic and industrial uses and then, in more detail, impact from an area or regional standpoint which involves all water uses. Both domestic and industrial users might incur added costs in using water polluted from return flows. Since water usually has higher values in industrial and domestic uses than in agricultural use, and involves smaller quantities, several courses of action are more available than in the case of agriculture.

The downstream relationship gives rise to the basic externality problem. Incidence of benefits and costs arise. Institutional and financing arrangements for adjustments are prominent problems. Cost allocations are difficult. Non-economic uses of farm and other resources arise because of distortion of cost structures by disassociation of benefits and costs. Some conceptual work is available on solution of the externality problem. But concensus does not exist on the prominent proposals.

Local and regional economies

Changes in the quality of water used for agricultural and other purposes have impacts on local and regional, as well as national economies. These changes produce either beneficial or adverse effects, depending on their nature and magnitude. In resource evaluation terminology, the effects are called secondary or indirect benefits or costs. Like primary effects, they can be tangible (monetary) or intangible. Public resource development agencies have long recognized these effects in their project evaluations; e.g., the Bureau of Reclamation has an explicit procedure and criteria for assessing dollar value and for describing non-monetary effects. Senate Document 97 (222) recognizes secondary benefits in public investments to a greater extent than did the Interagency Report (223). Views vary, from no recognition of secondary effects to placing great importance on them but they have gained increasing attention in recent years. A controversy hinges primarily on the question of national vs regional goals in resource development. No one doubts the local worth of resource development, but it is argued that these effects cancel out at the national level. Even assuming that the latter view is correct, a particular development can be considered at the local level in terms of effects, beneficiaries, and payments of investment and project costs.

The input-output model is a means of recognizing and estimating total effect on local economies of particular investments. This model includes total economic activity and recognizes inter-relationships between sectors and industries in the economy and the impact that each has on the other. Basic direct effects or damages are estimated outside the model and injected to arrive at a new transaction table and new set of coefficients. The model then estimates total indirect effects through the economy. Some direct and all indirect effects are expressed in total gross output (dollars), and to the extent that this measure serves the purpose, procedurally it is an adequate approach. However, gross value output does not meet many needs in resource evaluations. A net change is frequently needed. It is not evident yet whether data and coefficients that are available for I-O analyses are sufficiently refined to permit the degree of "accuracy" needed with reference to an investment that may be small compared with total economic activity in the model.

The Colorado Economic Base Study utilized the I-O model for estimating damage costs under various quality situations. Both direct and indirect damages were defined for two fairly large sub-basins.

Alternative Courses of Action

Appraisal of these alternatives is part of the income and adjustment features reviewed above. The major possibilities include:

1. Decreased total gross output -- lower incomes and crop yields.
2. Treatment of water.

3. Dilution through increased purchase and use of water.

4. Bypass channels resulting in less water of improved quality.

5. Other increased input and consumer costs.

6. Use of less water in upstream areas.

7. Enforcement of standards in return flow quality. This alternative is dependent on several others in the listing.

Where alternatives are physically feasible, economic appraisals are needed. Where only one possibility exists, estimates are needed of the economic impacts of this course of action. The Colorado Economic Base Study (219) appears to be a single effort of this kind where agricultural water quality problems prevailed. The appropriate value or price of water to use, especially in analysis of dilution and treatment alternatives, poses a difficult problem in many areas. Frequently a water market is not operational, so actual market sale prices are not available. Payments and costs being made or incurred by companies and districts probably do not coincide with actual water values or with prices that would prevail in an active market. This problem proved to be especially troublesome in the Colorado Economic Base Study.

"Optimum" levels of water quality

Analysis of this goal would be part of the appraisal of alternative levels of water quality and of alternative courses of action. It is significant in establishing public standards of water quality. Both economic and institutional elements are involved -- what is economically feasible and desirable conditioned by institutionally permissible adjustments and standards.

Levels and enforcement of water quality standards should be consistent with established national and regional goals of economic efficiency and other criteria. Achievement of this consistency involves consideration of both benefit and cost functions. If the standards do not achieve this purpose, serious misallocations of resources could result. To date, standards have been set on the basis of judgments and criteria largely other than economic, at least in an explicit sense. This situation applies especially to agriculture and quality of water.

Institutions

Physical and economic appraisals are basic to water quality appraisals and adjustments. However, farmers and others frequently encounter obstacles and limitations in effecting adjustments even though desirable economically. Institutions that either hinder or help relate to investment and operating capital, water shortages, water rights and appropriate organizations for group action. The Water Quality Act of 1965, Public Law 89-234, amended the Federal Water Pollution Control Act to provide for the establishment of water quality standards for interstate water. Levels of quality established could influence economic activity in areas where maintenance or improvement of quality poses difficult adjustment problems to the users.

Selected Research and Literature on the Economies of Irrigation Return Flow and Water Quality

The Colorado Economic Base Study was a joint effort of FWPCA, several universities, and the Economic Research Service, USDA (219). It was a large investigation in terms of budget, personnel, time, and content. The input-output inter-industry technique was applied. Separate base and projections analyses were made for six sub-basins within the Colorado River Basin. The overall objective was to develop an economic framework within which appraisals could be made of impacts of water quality deterioration and water quality control measures, investments and adjustments. The study and technique were extended to estimate damages for two sub-basins -- Lower Main Stem and Gila -- where the analysis indicated that water quality deterioration would further constrain economic activity in 1980 and in 2010. This study is significant both in procedures and content. In the two sub-basins where quality deterioration may be substantial in the projection years unless total water supplies are augmented, four major results were identified:

1. Reductions in output and total gross income in agricultural sectors.

2. Increased cost of more water.

3. Increased household purchases of soap.

4. Increased treatment costs in industrial sectors.

By introducing costs and other direct effects into the input-output models under no quality constrained conditions, the indirect effects of lowered water quality were estimated for each of the above results in these two sub-basins. The study did not analyze specifically the impact of alternative adjustments or control measures on areas or sub-basins. Nor did it specifically analyze the return flow problem. However, in these sub-basins, irrigation is the major water use and re-use of lower quality return flow water is a major problem.

As a segment of the Colorado Economic Base Study described above, the Economic Research Service made an analysis of agricultural impacts with reference to the Wellton-Mohawk area in Arizona (220). Basically, Pincock analyzed the production, cost, and income effects on farms in this area under three levels of water quality: 800 mg/l, 920 mg/l, and 1,233 mg/l. He used a crop enterprise and farm budget approach. The analysis was based largely on experimental data and informed judgments with respect to production and damage functions. Briefly his conclusions were:

1. No cropping pattern changes would occur within the range of 800 to 1,233 mg/l.

2. Additional leaching water would not be needed.

3. Major effects would be decreased crop yields.

4. Net damage effects would be small at 920 mg/l but large at 1,233 mg/l.

Pincock did not consider the return flow problem, although use of return flow water is a primary element of deteriorated water quality. His study does point up the adequacy and inadequacy of present data for this kind of analysis with reference to the Lower Colorado River Basin. This study was a basic input to the appraisal of damages to agriculture described for the Colorado Economic Base Study.

Kneese has been a major proponent of the "basin firm" concept for internalization of external economic effects (224). This approach applies certain management principles of farm or business firms to a total basin, to gain maximum benefit in dealing with water quality problems in the basin. Several possibilities exist for dealing with economic externalities:

1. Internalize the externalities.

2. Adopt a system of charges or payments.

3. Enforce water quality standards.

With reference to irrigation return flows, the "basin firm" concept would likely require group action which action could accomplish adjustments through a system of charges, incentive payments, and enforcement. Others have recognized the potential. Castle (225) emphasizes the need for institutional or administrative design to accomplish what the market fails to do. Wantrup (226) has questioned the usefulness of the "basin firm" concept. Rather, he suggests that policy should emphasize economic functions employed by firms which cause pollution. Among these policies and functions are:

1. Prohibit certain production functions.
2. Require certain production functions.
3. Impose quality standards on discharge.
4. Have unified collection and treatment of waste by public, e. g., irrigation drains.
5. Give economic incentive through tax relief, loans, rebates, grants, etc.

Research in process

Some encouragement with respect to economic alleviation of water quality problems is to be found in current research (227). Titles of research projects sometimes include "irrigation return flows." However, one concludes from the research currently under way that this subject is not yet a major element of the total economic research program.

In the past several years, the U. S. Department of Agriculture in cooperation with land-grant colleges has devoted substantial attention to delineating significant research problem areas including:

1. Management of salinity and saline soils -- problems relating to salt accumulation, leaching, and degrading water downstream.
2. Economic and legal problems in management of water and watersheds. Among items of emphasis are improved benefit-cost methods for identifying and quantifying relative economic efficiency of development and relation to national needs and objectives, and improved legal and institutional arrangements, including cost-sharing.

3. Alleviate soil, water and air pollution. Character, intensity and causes of pollution from agriculture and forestry, alternative methods of reducing and controlling, and use of low quality water for agricultural purposes.

Secondly, a review sponsored by FWPCA of research needs is noted (229). This report emphasizes the lack of adequate research and data. Socio-economic problem areas include pollution abatement costs, water treatment costs, and benefit-cost studies of economic effects. The Western Agricultural Economics Research Council of the Western Agricultural Experiment Stations, through its Committee on Economics on Water Resources Development, has recommended and obtained approval for a regional research project on the economics of water quality.

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LEGAL ASPECTS

Legal Framework for Irrigation Water Use

Orderly water development and stable and efficient utilization over long periods of time require the establishment of ground rules setting equitable bounds on the way water can be used. Such rules or laws must ideally encourage the full development and use of water resources while prohibiting wasteful and harmful practices. They should be non-discriminatory and durable in accommodating transitions in use, to help avoid the danger of conflict developing.

Generally, water has been considered to be the property of the public, yet made available for individual use while protecting both public interest and individual rights. Certainty of the right is a basic necessity in any water law. Water has been viewed from the beginning of American water jurisprudence as a right of property, to which protection is afforded by provisions of the federal and state constitutions. For its stability, utility, and transferability each water user deserves a clear statement of his rights through a system of title recognized under law. To this end, individual states have evolved statutory and administrative procedures for acquiring water rights, considering protests, specifying conditions of forfeiture, adjudicating water rights, and maintaining a central registry of water rights. These state-developed codes have been and still are an indispensable basis for decision and action to permit orderly and equitable expansion of uses while carefully safeguarding existing rights--whether these be individual, mutual, state, or federal. Quality always has been a consideration in water rights, but its emphasis is of more recent date. Population pressures naturally prompt water quality concern, including regulations.

Legal and hydrologic compatibility

To be durable, a water law system must have a conceptual structure harmonious with hydrologic laws and principles, including considerations of quality as well as quantity. The legal character of water rights must be developed from an understanding of the nature, occurrence and movement of water. Water is characterized by dynamism, complexity, and unity. All three characteristics have

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created trouble for water law-makers. Law can be more precise when dealing with such fixed quantities as real estate. The transient, cyclic, and renewable nature of water requires a different adaptation in law. In an attempt to simplify the complex and poorly understood interrelation of water within a drainage basin, courts have classified water in various ways. Unfortunately, such classifications often are completely unharmonious with the existing hydrologic relationships. Water rights based on hydrologically unsound classifications and definitions are insecure and lead to confusion and additional litigation.

All water in streams, lakes, swamps, and underground comes from precipitation. Topography, soil porosity, geologic formations and configurations, and other factors affect the path and rate of movement of water over and through the soil mantle in response to gravity. These factors also affect the mass inputs of dissolved and suspended materials carried in a water supply. Flowing in natural patterns, water is a transporting agent for these substances. This transport aspect of the hydrologic cycle becomes crucial in consideration of water quality management. Water is subject to continuous evaporation and transpiration which decrease its volume as it moves. Hydrologically, a river is in unity with the landscape it drains. The visible river is only a part of the complete drainage system. Surface streams and rivers are connected with "ghost rivers" that flow slower beneath streambeds and through the porous media of the entire watershed. It is in this connotation that we speak of the "hydrologic unity" existing in a river basin. Many courts in their decisions obviously have failed to grasp this notion.

A river system has a "dynamic equilibrium" in its pattern of occurrence and movement of water. This pattern is specific to a particular river system, giving rise to the hydrologic truism that "every watershed is a law unto itself." But legal adaptation to this has been difficult.

Since natural flow patterns often do not conform to desired use patterns, man modifies the natural system. Without such modification, social and economic potentials could not be realized. Changes in flow pattern, made by the construction of physical works to store, convey, and treat water, are translated to downstream locations. There may be increased loss of pure water to the atmosphere, and generally there is an addition of suspended and dissolved substances. As water is returned to the system after a particular use it becomes available for re-use downstream, but the original flow pattern is modified, to varying degrees, in terms of quality, quantity, and regimen. Certain uses have an imperceptible effect on downstream uses, but others have a significant effect, on the amount, timing, and quality of water available to subsequent users. Therefore, water development and administration must consider the total system. Legal boundary conditions should not restrict the utility of the resource, but rather maximize it, and provide positive protection and certainty to each user in regard to later uses.

Water rights doctrine

Water law in the West is mainly irrigation law, although mining activities had an early influence on the laws (23). Irrigation generally involves substantial diversions from streams or other sources and conveyance to selected lands regardless of whether or not these lands are contiguous to the source of water. It has been believed to be in the public interest that every possible acre of land be irrigated. Thus, there has been an intensive and extensive use and a multiplicity of uses, so far as the water supply has permitted. "It is understandable, therefore, that the water law of the western states presents a complexity of pattern and a fullness of development not to be found in the law relating to water in the East" (10). On the other hand, those regions of plentiful rainfall have had a natural distribution of water which precludes or reduces the need for irrigation. In such regions the emphasis has been on the right of the contiguous landowner to have the water flow past his property in approximately its natural state, substantially undiminished in quantity or quality. When one contemplates the variety and kinds of economic enterprises requiring water at specific locations in any region it is extremely difficult to see how any portion of the United States could survive under a law that would forbid use of water on land or at locations not contiguous to a stream. Actually, doctrines prescribing this generally have been modified or circumvented by legislative enactments in most states as necessity for more reasonable interpretations have developed.

Riparian and appropriative doctrines

There are two basic systems of water rights in the United States: riparian and appropriative. They are extensively treated in many scholarly writings (10, 230, 231). The doctrines fundamentally are quite different. The essential differences have been outlined by Clark and Martz (232):

> In both riparian and appropriation doctrines, a water right is regarded as "usufructuary," a right of use and not an interest in the corpus of the water supply. But riparian rights originate from land ownership and

> are dependent on physical location, i.e., contiguity of land to a body of water. Appropriative rights do not depend upon land ownership. They are acquired by actual use of the supply and do not exist without such utilization. Riparian rights, in contrast, remain "vested" though unexercised. In general, riparian owners may not exercise their water rights on riparian lands. Appropriators may use the supply without regard to location.
>
> Appropriative rights are fixed and certain as to the amounts of water allocated because of the principle which entitles the senior water right holder to take his allotted quantity before junior appropriators may take theirs. In short "first in time, first in legal right" governs. Riparian rights are not lost by non-use because they are an interest in particular land. Appropriative rights are terminated by non-use or abandonment because their legal existence was created by actual use only.

There are many extensions and refinements to the two doctrines. The law of appropriation has the same basic ingredients in each state. The riparian doctrine has undergone modification which permits more comprehensive use of water. Such modification has brought the doctrine closer to the appropriation doctrine and in more realistic compatibility with the hydrologic facts of life. The degree of modification in each state seems to be correlated with the pressure for water development and management in the economic and social growth of the state. In arid areas where good land is much more abundant than water, the appropriation philosophy of water rights generally has been adopted. In locations where resources other than water were limiting factors to economic development the riparian doctrine or common law has been the basis for water rights. While the jurisdiction of either the appropriative or riparian doctrine has been paramount in most states, some have recognized both systems. Inasmuch as these two systems of law are quite different it was inevitable that in states recognizing both systems many conflicts and extensive litigation developed. The riparian rule is a judicial rule. Legislation on riparian water rights has either abrogated, limited, or modified the doctrine. The doctrine of appropriation, on the other hand, is based upon specific statutes which originally codified local customs. Court decisions have dealt principally with interpretations of the customs and laws and with constitutional questions (232). Many courts in upholding the riparian doctrine have viewed the subject from the standpoint of private property rights. Recognition of public interest has been a slow and difficult process.

Though far from perfect, the doctrine of appropriation has proved more workable than the riparian doctrine in development and use of water resources. It is far less restrictive, affords greater protection to investments in water enterprises, and includes the essential element of "beneficial use." The aim of the latter requirement is to safeguard public interest in use.

State water right structure and administration

Originally, all means of appropriating water (in western streams at least) were non-statutory; that is, there was no federal or state statute outlining the steps in acquiring the right. Local customs governed the appropriation of water. With further use of water and the impetus of federal development through the Carey Act, the Desert Land Act, and the Reclamation Act, formal appropriation procedures became necessary. Thus, a complete administrative system pertaining to water rights in the West originated in the need for legal procedures to control the use of water resources. Elwood Mead (232) helped to pioneer a complete state system of supervision over the appropriation, adjudication, and distribution of water. The administrative system Mead began in Wyoming spread rapidly to other states. While most states have undergone occasional reorganization to discharge statutory functions more effectively, the conventional functions have remained about the same. Generally, these functions are vested in a state engineer as the chief administrative officer. With statutory guidelines, he makes decisions on applications to appropriate water, but his actions are subject to judicial review. The state engineer also has power to administer the water supply, both surface streams and groundwater, at any given time and place, considering the hydrologic variability of the system and the priority needs of the state. In some states these functions are performed by a board. An aspect of increasing value in a centralized administrative procedure has been the maintenance of uptodate records in a single state office.

Interstate compacts

Compacts between states have been executed with respect to the use of water of several interstate streams. Only congressional consent validates such a compact. It is drawn up by representatives of the states concerned, with the concurrence of a representative of the federal government; ratified by the respective state legislatures, and approved by an act of Congress.

The Supreme Court has recommended that the differences between states concerning the use of their common rivers be settled by compact where possible. In various instances this has been done. In other instances protracted negotiations failed to compose the differences and court action was resorted to. Court action, or judicial apportionment, is sometimes referred to as the "contentious approach." Interstate compacts are said to provide the "cooperative approach" to the same problem. In the case of Colorado vs Kansas, 320 U.S. 383, 392 (1943) the Supreme Court said:

> The reason for judicial caution in adjudicating the relative rights of states in such cases is that, while we have jurisdiction of such disputes, they involve the interests of quasi-sovereigns, present complicated and delicate questions, and, due to the possibility of future change of conditions, necessitate expert administration rather than judicial imposition of a hard and fast rule. Such controversies may appropriately be composed by negotiation and agreement, pursuant to the compact clause of the Federal Constitution. We say of this case, as the court has said of interstate difference of like nature, that such mutual accommodation and agreement should, if possible, be the medium of settlement, instead of invocation of our adjudicatory power.

The Colorado River Compact of 1922 was probably the first major interstate participation in regional water supply allocation. Significantly, this compact superseded the "first in time first in right" principle by preserving a defined amount of the river basin water supply for future development and use in the so-called Upper Colorado Basin states. This agreement made possible the immediate construction of Hoover Dam and Lake Mead to start meeting immediate demands of the lower basin area. The basic allocations of this compact have survived a 40-year lag in upper basin utilization of the compacted water supply. It is important to note that storage and irrigation return flow are looked to by the upper basin states to meet downstream compact commitments.

Most regional water development to this time has been accomplished after compacts and/or judicial decrees have been consummated. There probably are more than 20 interstate water compacts dealing with various aspects of water allocation and development. Two-thirds of these are in the West. Two fundamental concepts seem to permeate all compacts or decrees having to do with interstate water control and allocation. The first is an unequivocal recognition of existing valid water rights in force under the applicable laws of the specific states involved. The second requires protection to a "basin of origin" in the form of a fair water allocation and a protection of that allocation in the operating arrangement dealing with unappropriated water, regardless of time of future-use (233).

Federal Views on Water Rights

In recent decades much has been said concerning federal-state relations in water rights. Actually, there is no federal law of water rights in contradistinction to that of states. Only the states have developed codes and institutional machinery to regulate the use of water. The uneasiness or controversy that has been engendered is of fairly recent origin and stems from Supreme Court decisions and Justice Department assertions that unsettle traditional state understandings.

The federal view has its basic premise in the supremacy clause of the Constitution which prevents states from limiting the authority of the United States over its own property. The federal view is largely one of sovereignty which questions whether a state should have the right to regulate and control the actions of the federal government in water matters and whether the application of federal laws of waters within a state should be limited by the laws of a state. Both state and federal governments have similar objectives in serving the public interest. Water development programs are not for the aggrandizement of any sovereign entity, either federal or state. Hence, there is no necessity for any real clash between federal and state governments. The focus should be on providing legal and institutional machinery to facilitate and promote orderly and equitable water development in the public interest.

One of the issues of federal-state controversy is concerned with compensibility of water rights taken by the United States relating to any navigable streams. It seems obvious that government control over "navigable waters" would be meaningless if the tributaries could be dried up one by one so that eventually the navigability of the stream could be destroyed. Hence, it is necessary for the federal government to have control over non-navigable headwaters as well. The federal position is that it should not have to pay for what has always been its own property. Being the original proprietor of the public domain the United States acquired all water rights on those lands. Justice Department attorneys claim, therefore, that unless conveyed away, such land and water rights are still U. S. property, and any such conveyance must have been by an act of Congress under the property clause. While certain federal statutes such as the Desert Land Act, provide that water rights may be acquired by complying with state laws, this does not invalidate the federal argument that ratification of state constitutions did not transfer authority to convey title to water. One still proves his title to water rights as he proves his title to land by tracing his title through intervening owners to the United States of America. In instances where just compensation has been an issue the federal government has asserted that unless public rights have been relinquished there is no obligation (234).

Another major problem relates to the federal claim of water rights appurtenant to lands reserved from the public domain. Winters vs. United States (207 U. S. 564, 52 L. Ed. 340, 28 Sup. Ct. 207) has been described as the historical antecedent of present proprietary claims. This case had the effect of establishing that a reservation of lands by the United States also reserves such water as may be required to carry out the purposes of the reservation. While the Winters case had to do with an Indian reservation, Justice Department attorneys contend that the power of the United States to reserve water for lands withdrawn extends to all types of reservations. In the Santa Margarita Water Company vs. United States, the government position was stated:

> The United States of America claims that the title to the rights to the use of water upon the reserved lands of the U.S.A. resides in it and has never been conveyed away. Those rights are part of the land and may be administered by the U.S.A. independent of the laws of the several states. They are in some regard similar to state-recognized riparian rights as use does not create them and non-use does not cause their loss, yet to the extent they are required to meet the beneficial uses for which they were reserved they are not subject to diminution by appropriative or riparian rights which vested subsequent to the reservation. They differ from appropriative rights as they exist as parcel to the land and require no act on the part of the U.S.A. to initiate or maintain them. These rights have been reserved by executive orders and statutes.

The states have pointed out that their constitutions provide either for state ownership or state plenary power over all water within the state; that such constitutions were ratified by Congress when the states were admitted to the Union; and such action constitutes in substance, if not actual conveyance by the Congress, at least a compact with the admitted state. States also refer to a long line of congressional acts recognizing the state laws of water as further confirmation of the intention of Congress to treat the waters of non-navigable streams as being under state jurisdiction. Viewed from the states' position, the federal government is now asserting control over and ownership of all the water in the western United States arising on federal reserved lands so as to put in jeopardy water rights recognized under state water law.

It is rather significant that both the state and federal positions seem to be conceived in terms of power and authority. For the past several years legislation has been introduced in Congress to declare, reform, clarify, amend, modify, confirm or restate the state and federal relationship in water rights. The struggle is basically over who becomes top dog so far as water development is concerned. To date none of this proposed legislation has become law. Based on considerations of constitutional law, the federal position may be rather formidable. In terms of logical validity in squaring with the hydrologic facts of life and the purpose of law and policy in the orderly and efficient development of water, the federal position leaves much to be desired. It leads to the application of unsound principles in the development and use of water resources. Claims based on appurtenance to federally owned land are a throwback to the riparian doctrine of water rights which has been found quite unsuitable in promoting efficient water development. It is a selfish position in that reserved amounts in federal ownership are unspecified in quantity, in nature of use, and in time when uses are to be initiated. In most western states the reserved federal lands are generally upstream from locations where most water uses occur under rights perfected under state law. Consequently, any capricious use or development of waters appurtenant to federal lands could alter the pattern of flow previously existing. A cloud of uncertainty develops over the rights of any users downstream from a federal reservation whose rights may be subsequent to the reservation. If the federal government has reserved unspecified amounts of water, for yet-to-be-determined purposes, which may be initiated at unspecified times, how do state planners tell how much water remains for development by non-federal interest? Must available supplies be wasted pending the time that reserved water may be ultimately utilized? How can individual states guarantee that interstate compact obligations can continue to be honored? Can recently constructed projects pay out before the claimed reserved water is utilized? How can managers, planners, and administrators integrate, coordinate, and optimize water uses in a total system context if the unspecified reservation of water leaves a "floating" boundary condition? If state developed codes for water allocation, protection, and definition of water rights are abandoned, what new and better ones are advanced by the federal government to replace them? It appears that the Justice Department -- an agency somewhat remote from real problems of water resource development, and having no administrative responsibility for a federal rights law if such were forthcoming -- is choosing to live by outmoded, outdated, and unworkable principles -- unless, of course, all future water development is to be 100 percent federally accomplished.

General Rules of Law Relating to Waste, Seepage and Return Water

There are only a few court decisions relating to the acquisition of rights in the re-use of water (235). A search of the literature bears out the relative silence of the law as relating to the acquisition and disposition of return water. Legal periodicals from 1960 to date indicate almost no information on the subject. The following summary has been based on exhaustive studies made on the subject by Wells A. Hutchins in cooperation with various western states in producing a number of volumes summarizing the law of water rights in the West (235-243).

Owners' rights on lands of origin

Continuance of supply. As a general rule, the owner of the land on which waste and seepage waters originate and from which they flow to other lands is not required to continue the conditions that lead to the supply of waste and seepage water. Exceptions to this rule may result when a permanent right to the use of waste water is obtained by purchase or grant, or if discontinuance of the supply is done wantonly or to harm another user. It may also be defeated by estoppel. Long continued use of water leaking from defective diversion works may result in the downstream appropriator obtaining a right against the owner of the works.

Recapture. The original holder of a water right who has never released title to the corpus of the water diverted in the exercise of his right may refuse to allow such water to pass beyond his land.

Water from a different watershed may be recaptured within the boundaries of the original project even after discharge in the natural stream channel that is being used as a temporary conduit.

A party cannot reclaim water that is considered abandoned or is discharged without intent to recapture.

Discharge of waste water. The right to discharge waste water upon other lands has been acquired by prescription. The right to discharge water into a water course is allowed provided it does not result in injury to lower landowners. Anything in excess of reasonable and non-injurious discharge is considered wrongful, but invasion of a lower landowner's rights may be prescriptive.

Users' rights to waste and seepage water. Generally, the same principles apply to the appropriation of waste, seepage and foreign water released into a stream with no intention to recapture as to natural flow. Waste, seepage, and foreign water is generally not subject to riparian claim in appropriation or dual system states. Since use of waste water is generally made after it has left the land and control of the original owner, in most cases it is impossible to obtain rights to such water by prescription. In most cases the use is either permissive or is not challenged by the original owner or user because he is not concerned with the use of water after it leaves his premises.

Return water

Appropriability. On many sources, including watersheds other than those in which it is originally diverted, return flow is considered an important factor in the supply for downstream users and it is subject to appropriation when no longer under the control of the upstream user. Rights of a senior appropriator, whose water is supplied by return flow from a junior user upstream, cannot change his right upstream above the junior so as to deprive the latter of the water.

Return water within the watershed

(a) Water returning to the stream from which diverted: Riparian rights. Riparian lands benefit from the return to the stream of water diverted upstream but unconsumed after use, and owners thereof are entitled to such portions of the natural flow diverted upstream as are allowed to flow back into the stream after use. The fact that such water has been once used on upstream lands does not deprive it of the character of natural flow. The claim of the riparian owner upon the natural flow of a stream is such that he may enjoin an upstream diversion out of the watershed where the return flow cannot return to the stream above his riparian lands. Appropriative rights. The original supply cannot be diverted out of the watershed if it deprives a lower appropriator of the use of return water upon which he has been depending in the exercise of his appropriative right.

(b) Water returning to an upstream tributary: The right of a riparian owner extends to the tributaries that enter the stream above his land. Hence, the riparian owner has rights to the return flow of water taken out of a watershed but which returns to the main stream above his land.

Return flow from foreign water

(a) Abandoned without intent to recapture: The principle that one cannot reclaim water that he has abandoned after rights of others have lawfully attached is a generally applied rule of law. It is said that the party who has released such water with no intent to recapture it has lost all interest in the water abandoned. Some distinction has been made, however, in the abandonment of released water as it related to particles of water and not to the water right. Montana has ruled that foreign water becomes a part of the stream.

(b) Subject to appropriation: Where those who have imported foreign water and released it into a watercourse make no claim to its further use, such water does not accrue to riparian owners and appropriators but generally becomes subject to appropriation in order of priority by those who can gain access to it. These appropriative rights attach only to such foreign water as has been abandoned and usually are subject to the right of the importer to cease his abandonment thereof in whole or in part. These rights also usually are subject to contingency that the supply may be intermittent or may be terminated at the will of the producer. Nevada statutes do not provide for the appropriation of waste water unless it reaches a natural channel. The importer may sell or otherwise dispose of his imported water at any time before abandoning the same.

(c) Not subject to riparian rights: Riparian rights do not attach to foreign water abandoned into the stream to which the riparian lands are contiguous. Although riparian rights do not attach to the return flow from foreign water, yet water from one tributary of a stream, taken across a divide and discharged into another tributary of the same stream, while foreign to the watershed into which it is introduced, is not foreign with respect to riparian lands lying on the main stream below the confluence or mouths of both upstream tributaries.

Rights of those who import foreign water

(a) Return flow not abandoned by producer: The fact that water is brought into an area from a different watershed and is relinquished or lost by discharge without intent to recapture does not constitute abandonment of the water right. The fact that importers have abandoned the flow from foreign water in the past is not usually taken to mean that they must continue such abandonment in the future.

(b) May terminate abandonment after others have appropriated abandoned water: It is a general rule that a producer of an artificial flow is for the most part under no obligation to lower claimants to continue to maintain the flow.

(c) Right of disposal by contract: As a general rule the producer of return flow from foreign water may dispose of the same by contract prior to abandonment of the flow. Appropriative rights that have attached to water abandoned in the past are not infringed upon by such acts.

(d) Exercise of right limited to reasonable beneficial use: Reasonable use governs the flow from foreign water as well as other water.

Discharge into natural channel. Those who bring foreign water into a watershed have the right to discharge the same, in a reasonable manner and without injury to others, into natural water courses.

Legal Recognition of Water Quality Criteria

In the evolvement of water law -- both case and statutory -- primary emphasis has been placed on considerations of quantity more than quality. Nevertheless, the matter of diminution of water quality has always been of concern, and in both the riparian and appropriation systems of water rights there is recognition that the right to use water pertains to its quality as well as to its quantity. Generally speaking, however, concern has been with protection from quality loss causing substantial harm and/or nuisance. Slight inconvenience, annoyance, or harm not greatly impairing usefulness, has generally been considered acceptable. The test of whether pollution complained of is wrongful and actionable has pivoted on whether it was excessive so as to be unreasonable (235). Even today, most state pollution control laws try to protect against the kinds of pollution that clearly and severely impair the the usefulness of water courses.

The riparian doctrine of water rights has generally undergone modifications to permit greater utilization of the flow. A strict interpretation of the riparian doctrine (the natural flow theory as opposed to the reasonable use theory) suggests the ultimate in pollution control. "Water flows and ought to flow as it is wont to flow" is a phrase often quoted from an early decision which sums up the basic tenets of the riparian doctrine. Since the objective is to preserve the integrity of the natural flow, any use that impairs the natural quantity or quality of the water cannot be allowed. If utilization of water resources are to be permitted or promoted then the doctrine must be relaxed such that the right protects the holder from unreasonable interference with his use. The "reasonable use" theory of the riparian doctrine suggests that so long as the impairment does not interfere with beneficial use it cannot be unreasonable. An important factor in determining the reasonableness of pollution by a riparian use is the social value of the polluting use compared to the social value of the injury.

Implicit in the appropriation doctrine, also, is a protection of water quality. An appropriative right would lose its superiority if at some point in time a junior appropriator were permitted to pollute the water supply so as to cause substantial injury to senior appropriators. Otherwise, the prior appropriator's right would no longer be superior. While the protection against deterioration of water quality accorded the prior appropriator is well established, the protection is circumscribed by the purposes specified for the use of water under his appropriation.

Every appropriation includes a definition of not only the quantity allowed but also the particular nature or purpose of the use. For example, a prior appropriation to use water for an irrigation purpose does not afford protection of quality that may be needed for domestic purposes. On the other hand, a permit which specifies the quantity and nature of use implies that the prior appropriator may cause such impairment as the use might normally be expected to cause. Thus, a prior appropriator may deprive a subsequent (potential) appropriator not only by depleting the supply but also by destroying its usefulness, having impaired the quality (244). Actually, this aspect of an appropriative right has been negated in the case of industrial and municipal uses by separate sets of rules promulgated to deal with water quality separately and specifically. However, so far as irrigation uses are concerned, prior appropriators have not been protected from deterioration in quality occurring in the irrigation process itself. Subsequent appropriators may be permitted to use the water and thereby lower the quality but their use must be beneficial and the injury resulting from the deterioration minor. As with the riparian rule, the social interest or public interest becomes a factor in the determination of an injury problem.

State water quality management

As water pollution problems have multiplied most states have established control agencies separate and independent from the agency traditionally charged with allocating rights to water use. The jurisdiction of such control agencies is generally broad, covering all water in the state, as do the water rights agencies. Quality and quantity problems are inseparable, and California wisely has recognized that jurisdiction over water quality should be correlated with the function of allocating water quantity.

Most states now include all or part of the provisions of the Suggested State Water Pollution Control Act (U. S. Department of H. E. W., revised 1965). Each state has developed rather strong statewide goals in water quality management. State policies have been developed and expressed in water codes and standards. These will not be detailed nor reviewed here except as they enter into considerations of irrigation return flow.

Much of the impetus for setting state standards and tighter state regulations on water pollution has stemmed from the 1948 Federal Water Pollution Control Law and subsequent amendments. The most notable amendment was in 1965, known as the Water Quality Act. This act contains provisions that illuminate some rather basic problems and philosophical issues with water quality management, especially irrigation.

Legal Conflicts Between Irrigation Water Rights and Water Quality Standards

The Water Quality Act of 1965 indicates that standards of water quality must be such as to protect the public health and welfare and to enhance the quality of water. In establishing such standards, the use and value of public water supplies, propagation of fish and wildlife, recreational purposes, and agricultural, industrial, and other legitimate uses are to be considered In setting guidelines for the formulation of acceptable standards the Secretary of the Interior emphasized the quality enhancement aspect by not allowing water quality to be degraded below existing levels. While agreeing with the intent of this so-called non-degradation policy, many states objected to the wording of the policy since it seemed to exclude considerations of "use and value," "practibility," and "economic" and "physical feasibility." In other words, enhancing the value of the water resources in the many uses specified in the act may be quite inconsistent with enhancing the quality per se. Water cannot be enhanced and degraded at the same time. A firm policy of non-degradation ignores physical and economic feasibility of complying with such a standard. The establishment of water quality objectives which purport to fully and adequately protect all existing and prospective beneficial uses may result in extremely costly waste disposal. In other words, the social costs may be increased by a strict interpretation of the non-degradation principle. Water uses demand different levels of quality and all water uses affect water quality to some degree. Full utilization of a water resource requires some compromise in quality enhancement. The non-degradation policy may be likened to the riparian doctrine of water rights. Both emphasize "naturalness" in the extreme. Both are unrealistic if utilization is an objective.

A strict policy of non-degradation presents a definite inconsistency in federal programs, also. Agencies such as the Bureau of Reclamation, U. S. Corps of Engineers, U. S. Department of Agriculture, and perhaps several others all have mandates to promote and perfect water utilization in ways which may cause water degradation. Both federal and state laws recognize that the use of water for irrigation is a beneficial use. Yet, the degradation of water quality through irrigation use is an inevitable consequence of the physical nature of that practice.

Mulligan (245) has pointed out that:

> There does not appear to be any economical and yet fully successful method available for the treating of irrigation waste waters in order to meet Control Board requirements for the discharge of these wastes to surface streams. In other words, it does not appear practical that irrigation return waters can be handled in the

> same manner as conventional, industrial or sewage wastes.
>
> In the case of sewage and industrial waste discharges from a pipeline effecting a relatively limited area, the control boards set requirements on either the waste discharge itself or the receiving waters or both. The discharger then constructs waste treatment facilities to meet the requirements established. The Control Boards check the discharge and/or the receiving waters for compliance.
>
> Contrast this with establishing requirements for agricultural drainage water for thousands of individual agricultural operations covering millions of acres presently irrigated and with potentials for irrigation of many millions of acres more. Add to this the fact that the effects of percolating agricultural wastes on groundwater quality are hard to evaluate which results in difficulty in establishment of regulatory requirements and you can readily see that the problem is one of great magnitude.

Agricultural wastes traditionally are discharged with no treatment to surface streams directly or indirectly following their cycle of use and re-use downstream.

The expressions of policy and intent for water quality management promulgated by Congress and implemented by the Department of Interior are appropriate and well intended. However, policies and procedures to implement water quality standards have shown a complete disregard for practical considerations of existing water right structure. Setting water quality standards can impair existing water rights and in effect perform a re-allocation of water within a given stream system. The setting of standards within a river basin may also cause imbalance in the sharing of the burden of water quality maintenance. The Colorado River serves as a good example, for the considerations are the same in any river basin:

Many years ago, the Colorado River Basin states recognized that because of the hydrologic unity existing in river basins all users should have their interests weighed in common. They subsequently attempted a compact dividing the water of the Colorado River among member states. Thus, in the common knowledge that orderly economic growth of the states served by the Colorado River System depended on having a known water supply from which to plan its developments, the states proceeded to divide the water. The 1922 Colorado River Compact failed to divide the flow of the river among individual states, but it did accomplish a division between the upper and lower basin states, with the gaging station at Lees Ferry as the dividing point. From the water allocated in the 1922 compact, the upper basin states spelled out the limits of utilization of each member state by the so-called Upper Colorado River Compact, consummated in 1948. Since that time each state in the upper basin has been free to re-allocate and administer the use of its Colorado River system water to any legitimate need in attempting to maximize the utility of available water within the limit of depletion allotments.

Over the years new uses have been made of Colorado River system water. Many more are contemplated. Each Colorado River Basin state has made tremendous investment in planning and development of its water entitlement. Each has made projections and long range decisions based on the certainty of their compact allocation and their water right structure. The problems in this basin arising from setting quality standards without reference to compact terms, hydrologic characteristics, and water rights structure, would be tremendous. For example, if dissolved solids concentration limits at particular points were set close to existing levels in accordance with the non-degradation policy, the TDS limit might well be exceeded before the depletion entitlement of the region upstream is reached. Thus, the arbitrary establishment of permissible salt concentrations could be in direct conflict with the terms of the Colorado River compacts or could result in the complete abrogation of them. Reasonable use and development by upstream users might be restricted because of the quality standards adopted at key points lower down the river system. To fix standards at present levels (in terms of concentration) would place the entire burden of quality control on those states which are still developing their water. They could only develop at considerable expense of treating or reconditioning effluents.

The incompatibility problem that can arise between quality standards and water rights might be paralleled by considerations of low flow augmentation as a remedy for deteriorating quality. As the process of use and re-use continues, chemical, physical, bacteriological, or thermal pollution may increase with each withdrawal. Concentrations become highest when flows are lowest. Consequently, provision to augment low flows, to reduce the concentration of undesirable constituents, is a desirable practice. Better regulation of natural streamflow so that dry season flows can be augmented would assure that critical water quality concentrations are not approached so quickly. Thus, a greater spectrum of users could be served and the utility of the supply extended. The Senate Select Committee on National Water Resources attempted to assess the amount of dilution water required (following treatment) to maintain generally accepted water quality for each water resource region. The volumes estimated were substantial.

Despite the stress placed on low flow augmentation and its obvious effectiveness for improving water quality, it generally has not been recognized as a legitimate beneficial use of water under state water law. The uses made possible by the augmentation practice would be recognized, but there is no provision for appropriation of water for dilution items. In a fully appropriated river basin where perhaps interstate compacts apportion allowable state depletions and state laws specify allocations to specific uses, augmentation may be possible only by rearrangement of existing water rights. As a result of the steady degradation in quality from upstream to downstream points, the need for flow augmentation would appear first at lower regions. Without import, augmentation may only be accomplished by restricting depletions at upstream locations so that greater flow volumes could proceed to downstream points. Conversely, if legitimate compacted or adjudicated water rights for specific uses at downstream locations are subsequently negated, not by lack of water availability but by quality deterioration, then their rights are surely invalidated. It is quite obvious that existing water right patterns and a river basin perspective must accompany any considerations of low flow augmentation.

The prevalent pattern of setting quality standards and implementing pollution control measures without regard to vested water rights can lead to serious conflict between and within states and regions.

RESEARCH NEEDS AND RECOMMENDATIONS

The preceding survey of literature justifies two generalizations: first, there is extensive literature indirectly bearing upon return flow; second, almost no basic research has been devoted to return flow, and only a little has been specifically concerned with return flow situations. There is need, therefore, for research that will answer many specific questions about quality and quantity of irrigation return flow.

New technology and continued introduction of new products such as pesticides and detergents demand continuing research to determine, in advance of their release for general use, any toxic effects of the products and the quality changes that affect the environment. Considerable of the fundamental research, such as that conducted on pesticide movement, degradation products, etc., need not be directly related to irrigation return flow in order to be applicable in an irrigation environment. But problems associated with salinity must be studied in the irrigation system.

No attempt has been made to establish research priorities, for gross difference exists in the magnitude of the problems. Availability of funds, equipment, and research capability must also influence the kind, amount, and rate of research.

Quantity of Return Flow

The quantity of irrigation return flow is dependent upon the following variables: quantity of irrigation water diverted; canal seepage and bypass water; water applied; time and method of application; precipitation; soil characteristics; evapotranspiration; type of crop, and farm practices. Each of these variables has been studied extensively, and approximate quantitative values have been assigned to each in relation to consumptive use of water and irrigation practices. Only a few of the parameters, however, have been specifically related to return flow problems. Nevertheless, with adequate data on the above variables, the quantity of irrigation return flow can be predicted with reasonable accuracy for most specified circumstances. Irrigation and drainage projects are designed on the basis of such estimates. But in any situation involving return flow, considerable effort may be required to adequately characterize the relevant variables. Additionally, while general estimates for a large river system may agree with observed data, the total system inevitably will have localities of excess water and others of deficient water, as well as areas of salt accumulation and leaching.

Recommendations

Past, present and planned research on the consumptive use of water, and on irrigation efficiency and drainage, precludes the need for general studies on consumptive use of water under the aegis of water quality research. The quantity of return flow from irrigation operations must routinely be included, however, as part of any investigations concerned with the quality of return flow waters.

In contrast, concepts and studies related to the potential "net depletion" of water supplies through irrigation usage have not been adequate to its importance. Net depletion of groundwater is especially difficult to quantitize. Diversion requirements and net depletion are the two variables most relevant to questions of return flow quantities. Social and economic costs associated with net depletion especially need studying.

Quality of Return Flow

Characterization and prediction of irrigation return flow quality are considerably more difficult than estimations of quantity, although the two are related. Like quantity, quality is dependent upon a number of variables. Most of these have been studied in other contexts. The principles derived, however, permit some generalization about the dissolved materials likely to be encountered in return flow water under specific conditions. Yet, there is no adequate conceptual model of how the quality changes as irrigation water passes through the soil. Until this has been developed, predictions of quality changes are largely speculative. Existing data indicate such a complex relationship between many of the variables that only further study of the specific variables will allow the development of more precise predictive equations.

The composition and quantity of the irrigation water applied are two determinants of the quality of return flow. Other major factors include the degree of increased concentration of solutes in the water and the reactions that occur between the point of irrigation application and that of return flow. The concentration of solutes in the soil is dependent on the timing and quantity of each irrigation application, the salinity and type of soil matrix, and evapotranspiration. Possible reactions include additions of new solutes as well as exchange and precipitation phenomena.

Recommendation

Intensive investigations are needed to bridge the information gap between the principles established in controlled research and theoretical calculations, and the actual changes in concentration and composition of salts in return flows as affected by the solutes in the irrigation water, soil characteristics, and management practices.

High priority should be given to the identification of sources of salinity entering the water of river systems. Analyses of such contaminant sources should provide bases for recommendations for reducing activities which contribute disproportionate quantities of salt to each system. Possibilities include the diversion of mineral spring waters from entering river systems and elimination of water entering and leaving highly saline, non-arable lands that provide high salt loads to stream channels.

Leaching and Salt Balance

The movement of salt in soil water differs in water-saturated and unsaturated conditions. Salts are leached more effectively from soil by water applied slowly and moving through unsaturated soil. Differences in salt movement associated with variations in rates of water application may provide guidelines for irrigation practices that can better control salt concentration in soil. A resultant effect on the quality of irrigation return flow water would be inevitable.

The salt contribution fron non-irrigated areas resulting from leaching residual salt by natural precipitation or canal seepage water may be important in evaluating salt balance in relation to irrigation. Decreasing diversions of water may reduce canal losses and excess irrigation applications that may leach salt from saline deposits or substrata.

Mineral springs often contribute significant proportions of salt load carried in at least the smaller river systems. Special toxic ions such as borates may be traced particularly to such sources. Ways should be sought to prevent such water from entering water of higher quality.

No models are available on which to base any reliable prediction of salt content of return flow water in a wide range of conditions. Serious preliminary formulations, however, will help in identifying systems that need more primary attention in more detailed studies. Present models of salt movement in the soil, such as the leaching requitement equation, are based on estimates of what the maximum salinity that can be tolerated by the crop or by the receiving water. Some elements such as boron are not readily leached from the soil and are being introduced into the water system as a result of detergent use by home and industry.

Recommendations

A comprehensive, reliable model should be developed of salt movement through soil profiles in relation to changes in quantity and composition of solutes, soil characteristics and irrigation, and other management practices. Parameters must be identified that will permit rapid evaluation of field situations and predictions of the quality and quantity of return flow water under a variety of conditions.

Systems methodologies for data collection and analysis should be developed for use in assessing the balance between water and salts applied to an area and the quantities leaving as return flow. Amounts entering the groundwater and/or leaving as surface flow should be carefully measured. The effects of climate, soils, crops and agricultural practices should be evaluated and considered vital components of each situation. The extent of salt removal from non-irrigated areas as a result of canal seepage or rainfall should be evaluated in developing salt balance concepts.

Intensive studies should be given to sources and effects of such toxic agents as boron, in streams carrying harmful quantities and the impact on agriculture when the water is used for irrigating crops.

The consequences of applying water at reduced rates that maintain soil in a less than water-saturated state need definition, particularly as related to soil leaching and the quality of return flow.

Mineral springs and other highly saline waters justify studies as to quantities and composition of salt contributed to stream channels. Possibilities for plugging, disposal, or alternative uses for such saline water merits further study.

Precipitation and Exchange Reactions

Precipitation and exchange reactions affect the quality of return flow water and are functions of the composition and concentration of salt in irrigation water, soil characteristics, plant influences, and agricultural practices. It is in this area that the basic mechanisms for understanding chemical quality must be sought. The precipitation reactions involve primarily calcium and magnesium carbonates, sulfates and possibly silicates. Carbonate precipitations are determined primarily by soil pH, partial pressure of carbon dioxide, temperature, and the concentrations of available calcium, magnesium, bicarbonate and carbonate ions.

Precipitation and exchange reactions alter the relative concentrations and thus the quality of irrigation return flows. Water carrying heavy metals, such as acid mine wastes, may be effectively freed from the metals on passage through soil, but the short and long-range effects on the recipient soil have not been carefully evaluated. Lead, copper and arsenic, for example, may have serious consequences when accumulated in soil, while zinc may be retained in substantial quantity in some soil before there is apparent crop damage.

The movement and retention patterns of such materials as fertilizers and pesticides are not adequately defined for irrigated soil nor are the contributors of these pollutants to return flow from other users.

Water containing dissolved phosphates are effectively freed from phosphate by passage through most soil. Nitrates, on the other hand, are not adsorbed by soil and move with the water. The primary nitrate sinks in a soil are usually considered to be plant absorption and microbial action.

Recommendations

Conditions associated with the precipitation of calcium and magnesium carbonates in soil should be evaluated in relation to theoretical principles, with attention to concentrations of calcium, magnesium, bicarbonate and carbonate in irrigation water, the carbon dioxide partial pressure in the soil system, pH, temperature, and other associated ions in solution. Special consideration should be given to defining the role of magnesium and its effect on carbonate precipitation and the SAR equation as it applies to the soil system.

Precipitation of alkaline earth silicates may sometimes be as important as carbonate precipitation in altering the ionic composition of irrigation return flow. The silicate composition of water and its implications require attention.

Soil adsorption of phosphates, heavy metals, or agricultural chemicals should be evaluated for resultant water improvement and the effects on the adsorbing soil and on crops grown in the soil. Changes in water temperature should be included as a variable.

Applied studies must establish major variables and methods for their measurement, such as will facilitate the quantitative evaluation of changes in dissolved solutes in irrigation water during the process of irrigation. Factors needing attention include evapotranspiration, cation and anion exchange phenomena, water temperature implications, plant interaction, precipitation and solution reactions, and related changes. These studies will require the monitoring of such parameters as the quantity and composition of pollutants in the irrigation water; the quantity, time and method of water application; irrigation efficiency; soil characteristics, including moisture and salt movement, its salinity status, and the exchangeable ions and organic-biological component of the soil; management practices, including fertilizer and pesticide treatments; and environment-related factors such as temperature, humidity, precipitation and evapotranspiration.

Translating to the Field

The vast accumulation of information on the chemistry and thermodynamics of solutes furnishes an excellent theoretical background about the complex relationships with solute changes that occur during the concentration and movement of salts in irrigation water through soil.

All pertinent variables must be carefully monitored, and to a major extent, controlled in new studies. Lysimeter experiments designed to evaluate all return flows on a year-around basis, would facilitate control of several variables. Intensive studies under selected field conditions with controlled soil conditions and agricultural practices should provide results validly applicable to diverse field situations.

Recommendations

Lysimeter or controlled field plot studies should involve irrigation of soils of identified characteristics with water of predetermined composition, under selected methods, rates and amounts of application at specified frequencies. Selected crops should be grown under these conditions and the significant factors controlled or measured, including the quantity and composition of water percolating below the root zone.

Detailed studies should be initiated under selected field situations in appropriate areas where groundwater originates, and where the most significant factors controlling the quality of return flow can be measured. The balance between water and salt applied to an area, the quantities leaving as surface return flow, and those entering the groundwater reservoir should receive attention. The effects of climate, soil, crops and agricultural practices should be evaluated as vital components of the systems involved.

Modern computer techniques have permitted analyses of our accumulated, extensive data on the composition of water of the United States. To capitalize upon the already substantial investment in such analyses, the data should now be further studied in relation to climate, geology, soil, and vegetation of selected areas.

Organic Wastes

Few organic wastes have received detailed attention in relation to quality of irrigation return flow. The effects on soil of large amounts of farm manure, and of organic wastes on drainage water composition needs study. Recent studies have shown feed lots to be a major source of nitrates in groundwater. Water containing sewage or other wastes may carry pathegenic organisms as well as decomposable organic materials. Organic materials may improve soil structural stability and permeability, and thus facilitate the movement of mineral elements, viruses, and possibly micro-organisms through soil.

Recommendations

The effects of decomposable organic materials on the quality of irrigation return flow and on the movement of such substances as phosphates, nitrogenous compounds and pesticides, and on the survival and movement of such organisms as viruses, pathogenic bacteria and nematodes should receive detailed attention. Studies should be made on all new pesticides to determine, in advance of their use, their persistence in soil, decomposition products, and the general reactions in soil, water and crops, and the resulting pollution hazards of the water coming from the land.

Thermal Pollution

Thermal pollution is a problem of growing importance. The role of irrigation in relation to thermal change is unknown. Under conditions of hot surface soil tail water may be warmed appreciably. Drainage water percolating through soil will usually attain the temperature of the soil substrata. The use of river systems for cooling in connection with both fossil fuel and atomic fuel power plants is increasing. Chemical reaction and solubility of salt in water are both directly and indirectly affected by the temperature. Carbon dioxide solubility is inversely related to water temperature and consequently thermal pollution may initiate precipitation reaction in either stream bed or soil.

Thermal pollution has direct effects on aquatic life. A few degrees change in temperature may drastically alter the proportions of biological systems. Return flows will most likely have an ameliorating effect on temperature extremes.

Recommendations

Thermal pollution or major temperature changes should be studied in terms of their effects on chemical changes in solutes. The role of irrigation in thermal pollution should be determined, as a moderator of major temperature changes as well as a positive or negative contributor of heat.

Matching Use to Quality

Disposal of low quality return flow water often is a major problem. . Some of it may best be used for wildlife marshes and for recreation. Evidence indicates that the economic return from such use may be high, but specifics are lacking. Information is needed on possible locations and productive management techniques for saline lakes or marshes, the uses to which they are best adapted, and monitoring methods and standards to protect public health.

The combination of well drained, permeable, sandy soil, liberal applications of water, and salt tolerant crops can permit crop production with water commonly considered unsatisfactory for agricultural purposes. Many possible combinations of these factors have not been adequately evaluated.

The technology of reclaiming low quality water is currently receiving considerable, well deserved attention. The imminent water shortages in large areas of the western United States and in other countries make efficient reclamation by distillation or one of the membrane processes a highly important goal. Reclaimed water both increases the quantity and improves the quality without increasing withdrawals from natural supplies.

Aquatic life water quality criteria have been established primarily for fish. Since fish are just one inhabitant of any body of water, there is information needed to provide more comprehensive criteria for water in relation to other aquatic life.

The large mass of analytical data on water quality of streams and well water provides an opportunity for detailed analyses using computer techniques. Data for various water basins can now be analyzed for trends and changes related to irrigation and agricultural practices. In some cases there is a large time lag in the effect of return flow on the quality of water being pumped from a groundwater basin.

Recommendations

The long-range result of mixing low quality return flow water with high quality water needs studying relative to the complete chain of water users. The quality cut-off point, at which the mixing of water provides no net advantage, needs to be established for different conditions. The advantages of recirculating reclaimed water in contrast to increasing withdrawals should be studied, using some specific cases.

A systems approach to available water basin data could help develop productive management techniques and philosophy.

Saline water has a significant but inadequately defined potential as a source of recreation. Investigations are needed to identify the range of uses and related considerations.

Use of different qualities of irrigation water should be studied under farm situations in relation to various soil and cropping conditions, and with special attention to new crops and varieties.

Effects of variations in water quality on plant nutrition have not been defined. Such studies can be expected to permit economic returns from water of quality now considered unacceptable.

Investigations of the technology of water reclamation should be continued, particularly using membrane processes.

The potential market for low quality water should be studied, with costs and other limitations carefully evaluated to determine combinations that can maximize economic returns.

Effects of salt and other chemicals on aquatic forms and biological systems should be defined and incorporated into relevant standards.

Organisms and species may provide practical indication to suitable use of water of reduced quality. For instance, the presence of certain fish indicates acceptability for livestock. Additional possible indicator organisms should be identified for other purposes, such as for the detection of shock loads of many pollutants.

Treatment and Management of Return Flow Waters

The pollutants in irrigation return flows that currently appear most objectionable, in terms of adversely affecting subsequent use, are nutrients, salinity and possibly pesticides. When established irrigation practices cannot be significantly modified to preclude eventual buildup of these constituents, treatment of irrigation return flows may be necessary to produce an acceptable quality level. If treatment is impracticable, the return flow may have to be physically excluded from sectors of the water resources when they would be objectionable. The hypothesis that users of irrigation water cannot afford to treat return flows needs re-examination in relation to total social and economic costs. If agriculture is to assume a posture comparable to that of municipalities and industry, technical and financial assistance undoubtedly will be required, to find practical and equitable solutions to the many problems and costs involved.

Recommendations

Studies should be initiated on the treatment requirements of irrigation return flow in terms of total quantity-quality systems management. Examples of the options that should be investigated include:

1. Collection and treatment to a specified level of nitrates, phosphates, and/or total dissolved solids, with eventual return to general water resources.

2. Dilution by streamflow regulation.

3. Management by diversion of return flows to selective uses where reduced quality is acceptable (e.g., industrial cooling water) or to disposal sinks (e.g., oceans, estuary, etc.)

4. Permutations of such possibilities.

Quality control decision-making must be examined in terms of a modern economic and legal framework.

Since formal identification of water pollution from irrigation return flows is a relatively recent phenomenon, substantial inputs must be made soon in the areas of manpower training, applied research of treatment technology, systems management planning, and federal and state legislation.

Groundwater

Our understanding of our groundwater resources is minimal. Most of what we do know simply emphasizes the need for research. As groundwater is pumped for irrigation, a deep percolating return flow changes the chemical composition of the groundwater. Deeply percolating water mixes with the groundwater resources and may be stored for long periods and eventually transported appreciable distances in groundwater aquifers.

Recommendations

Groundwater quality should be studied to help clarify changes in the composition of return flow. Procedure and equipment should be developed to permit the reliable sampling of groundwater and the systematic groundwater monitoring that should precede evaluation of groundwater quality in relation to possible use. Detailed study at selected locations should facilitate a comprehensive groundwater monitoring system to assess the long-term effects of irrigation on the quality of groundwater in the major storage basins.

Methodologies must be developed that will make possible adequate study of the composition of groundwater, its movement, patterns, rates and processes of mixing, and the gradual changes attributable to deeply percolating irrigation water.

The use of groundwater storage basins in managing irrigation return flows needs further study. In some instances unlined irrigation canals add appreciable quantities of relatively high quality water to the groundwater supply. The effects of conservation programs involving lining of canals that may cause changes in groundwater quality and quantity should be studied before canal lining and related programs are initiated.

The commonly observed quality-oriented stratification of groundwater within basins should be evaluated and mapped where practicable. Also, the rate of mixing of groundwater needs to be evaluated in relation to such factors as permeability of the soil substrata, rates and points of water additions and withdrawals, and other related factors.

The varied effects from moderate amounts of salt in irrigation water, including increased infiltration into slowly permeable soil, needs additional attention, particularly as related to irrigation practices and groundwater recharge.

Engineering techniques need to be developed to encourage more effective utilization of groundwater of varying qualities, for example, tapping better quality strata, while bypassing the less desirable.

Public Health

The public health aspects of return flow water will probably require continuous updating as new analytical techniques are developed for viral and other organisms, and as new chemicals are used in agricultural production. Some data indicate that nematodes and other plant pathogens may be carried by some return flows. A highly probable source of such contamination is runoff water from the soil surface, but confirmation is lacking. Salt and organics in irrigation water may influence the movement and survival of micro-organisms and the movement and decomposition of pesticides.

Radioactive pollution of water is a persistent and burgeoning problem. There is increasing danger of contaminated water being used for domestic and livestock consumption and for irrigation. Radio-nucleotides are generally strongly adsorbed by soil, and the water is thereby improved, but the effects on the soil and on the plants it supports have not been determined.

Recommendations

Factors affecting the rate of movement of viruses, bacteria, other micro-organisms and pesticides through soil, and their appearance and persistence in surface runoff water and groundwater should be determined. Conditions under which return flow water is likely to create health hazards should be defined more fully. The possibility of using selected organisms as indicators of water quality merits attention relative to public health problems.

Ways in which chemicals such as insecticides, herbicides and soil fumigants may become ingredients of return flow water and create potential health hazards should be determined and publicized.

Effects of radioactive pollutants on soil and the possibility of their uptake by plants and resultant consequences deserve attention relative to public health as well as to the agricultural productivity of the land.

Legal and Economic Considerations

Legal problems associated with deteriorating water quality have not been adequately investigated. Growing public concern over deterioration in the quality of many nationally important waters is leading to expanded legal consideration and action. The lack of appropriate legal structures relative to water quality may unnecessarily interfer with future water development projects and in some instances may hamper water quality control. To some extent the lack of legal frameworks for water quality control may be accentuated by the dearth of economic research to establish the cost of water quality deterioration. There is need for broad economic research related to water quality, to assess costs and benefits. Questions of equitable distribution of benefits to geographical and social sectors are likely to provide difficult moments unless legal guidelines are established.

Unique and extremely difficult economic problems related to irrigation return flows involve external economies and diseconomies. These problems frequently are referenced in terms of incidence of costs and benefits. Areas or firms or groups of firms that are interdependent in the physical use of resources, nevertheless, make their decisions independently. Thus, the cost and return functions of the water resources are distorted. In water quality, for example, the cost of deterioration in use instigated by one user may be borne by another user. Since the market system does not resolve these problems, institutional arrangements must be devised. Appraisal of economic impacts of various alternatives is basic to formulation of these programs.

There is need for more information concerning cost distribution and methods of financing systems required to serve users with the quality of water needed. In some instances it may be possible to exchange water between users and thereby achieve gains through matching water quality to users' quality requirements. New water agencies and laws may be needed to effect such changes.

Recommendations

Studies should be made to provide reference data that will enable greater precision in anticipating the physical, biological, social and economic consequences of alternative laws, public policies, and other institutional arrangements related to the use of water of different quality and the imposition of water quality standards, especially as related to irrigation return flow.

More intensive study should be made on the inseparable nature of quality-quantity management in relation to institutional, economic and legal restrictions, to assure that pollution laws do not abrogate existing water rights and compacts.

Inconsistencies in state and federal water laws and agency policies (as related to water depletion and pollution by irrigation and return flow) should be catalogued and plans developed for bringing them into general agreement. Agreement should be sought also between laws and policies and hydrologic principles.

The effects of changes in water quality on agricultural income, on land values and on costs of alternative ways of disposing of low quality waters should be investigated. Intensive research is needed on the economic, social and legal aspects of the effects of pollution, in regard to those who hold water rights.

A thorough economic model that relates water quality to uses and values would be a major step in assessing the economic costs or benefits of irrigation insofar as changes in water quality are concerned. Empirical testing of economic models, methodologies and criteria from the standpoint of farm, area, regional, and national impacts of water quality deterioration is essential. Studies of institutions and legal requirements for effecting such shifts in water to match users requirements also should receive attention.

Research should be done on assessments, financial arrangements, and sources for alleviating external diseconomies arising from the deterioration of water quality because of irrigation return flows and other uses of water. The costs of alternative procedures for disposing of and/or reclaiming saline return flows should be investigated. The economic and legal implications of biological contamination of waters by disease organisms, plant pathogens or other noxious pollutants also need attention.

GLOSSARY OF TERMS

Agricultural Consumptive Use: Use of water which is changed from the liquid to the gaseous state by evaporation or transpiration and is thereby lost from the soil-plant ecosystem. See also Evapotranspiration.

Applied Water Requirement: The quantity of water required to be delivered at a farmer's headgate in a given period of time to meet consumptive use and irrigation application loss requirements. It does not include direct precipitation.

Benefit-Cost Ratio: The arithmetic proportion of estimated average annual economic benefits to average annual cost, insofar as the factors can be expressed in monetary terms. It is a measure of the degree of tangible economic justification of a project.

Benefits: Increase or gains, net of associated or induced costs, in the value of goods and services which result from conditions with the project, as compared with conditions without the project. Benefits include tangibles and intangibles and may be classed as primary or secondary.

Bypass Water: Water diverted for irrigation, but returned to the river or source of supply without being applied to the agricultural land.

Bypassing: Quality control of public water supplies by conveying irrigation return flows in a separate channel thus bypassing the natural channel.

Concentration: The quantity of dissolved material in a unit volume or weight of water. In this report concentration is expressed in milligrams per liter, parts per million, equivalents per million, specific electrical conductance in micromhos per cm, and tons per acre foot.

Deep Percolation Losses: That portion of irrigation water applied to the land that percolates below the crop root zone and is not subject to consumptive use by the agricultural crops.

Degradable: Capable of being decomposed, deteriorated, or decayed into simpler forms with characteristics different from the original. Also referred to as biodegradable.

Degradation of Water Quality: Decrease in water quality due to increased concentration of any substance classified as a pollutant.

Dilution: The reduction of pollutant concentration of a given water by the addition of water having a lesser concentration of pollutant.

Drainage Water: Surface and subsurface water coming from irrigated areas which may be commingled with precipitation, surface runoff, and groundwater flow from non-irrigated lands.

Economic Demand Schedule: The price schedule of quantities of goods, services, or resources to be purchased.

Economic Efficiency: The situation in which productive resources are so allocated among users that any reshuffling from the pattern does not improve any individual's position but leaves all individuals as well served as before.

Evaporation Disposal: A method of treating undesirable return flows by capture and storage and allowing the stored water to naturally evaporate.

Evapotranspiration: The consumptive use of water from the soil. Water lost as vapor from a given area of soil through the combined processes of evaporation from the soil surface and transpiration from plants.

Financial Feasibility: A demonstration that beneficiaries are ready, willing, and able to pay reimbursable costs for products and services within the prescribed repayment period; that sufficient capital is authorized and available to finance construction to completion, and that estimated revenue to be derived during the prescribed repayment period is sufficient to cover reimbursable project costs.

Intangible Benefits: Those benefits which, although recognized as having real value in satisfying human needs or desires, are not fully measurable in monetary terms, or are incapable of such expression in formal analysis.

Intangible Damages: Those damages that cannot be evaulated in monetary terms, such as loss of life, suffering, etc.

Irrigation: As used in this report, the application of water to land to supply moisture required for the growing of crops. The application of water to land by man-made devices, structures or controls.

Irrigation Return Flow: Any water diverted for irrigation purposes that finds its way back into a source of supply (stream or groundwater basin). This includes bypass water, deep percolation losses, tail water runoff and seepage.

Irrigation Water: Water diverted from a surface or groundwater source to irrigate land.

Leaching Requirement: The fraction of water entering the soil that must pass through the root zone to prevent salt accumulation from exceeding a prescribed level, expressed as a percentage.

Maximization of Net Benefits: Extending the scope of development to the point where the benefits added by the last increment of scale (i. e., an increment of size of a unit, an individual purpose in a multiple purpose plan, or a unit in a comprehensive plan) are equal to the cost of adding that increment of scale.

Net Water Requirements: Applied water requirement less the amount of the applied water that can be salvaged and re-used within the area.

Nutrients: Compounds of nitrogen, phosphorus, and other elements essential for plant growth. (These may have an adverse effect on water quality.)

Pesticides: Chemical compounds used for the control of undesirable plants, animals, or insects. The term includes insecticides, weed killers, rodent poisons, nematode poisons, fungicides, and growth regulators.

Pollutants: Substances that may become dissolved, suspended, absorbed, or otherwise contained in water, that impair its usefulness.

Pollution: The presence of any substance (organic, inorganic, biological, thermal, or radiological) in water at intensity levels which tend to impair, degrade, or adversely affect its quality or usefulness for a specific purpose.

Primary Benefits: The value of goods and services directly resulting from the project, less associated costs incurred in realization of the benefits and any induced costs not included in project costs. Types of primary benefits may include domestic, municipal, and industrial water supply, irrigation, flood prevention, land stabilization, drainage, recreation, and fish and wildlife.

Project Economic Costs: The value of all goods and services (land, labor, and materials) used in constructing, operating, and maintaining a project or program; interest during construction, and all other identifiable expenses, losses, liabilities, and induced adverse effects connected therewith, whether in goods or services, whether tangible or intangible, and whether or not compensation is involved. Project economic costs are the sum of installation costs; operation, maintenance, and replacement costs, and induced costs. See also Installation Costs; Operation, Maintenance, and Replacement Costs; and Induced Costs.

Quality: The degree of excellence or conformance to standards for specific use.

Salinity: Salt content concentration of dissolved mineral salts in water or soil.

Salinization: The process of accumulation of soluble salts in soil.

Salt Balance: The quantity of salt entering an area by way of the irrigation water as compared with the quantity of salts removed from the area by return water.

Salts: Dissolved mineral matter and/or soluble inorganic salts.

Secondary Benefits: The increase in the value of goods and services which indirectly result under conditions expected with the project as compared to those without the project.

Seepage: That water which is lost from the conveyance channels of rivers or other water supply systems.

Sewage: The water-carried wastes originating from households (domestic sewage) and manufacturing establishments (industrial wastes) that are collected and transported in sewerage systems to treatment facilities. It contains organic materials that have high oxygen demands for degradation and decomposition.

Sprinkler Irrigation: A method simulating rainfall by using various spray nozzles to discharge water into the air allowing it to fall to the earth and infiltrate into the soil. Several designs are employed: solid set systems; portable systems; and hand held or positioned nozzles.

Sub-surface Irrigation: A method using the soil profile to transmit the water from the source of supply to its point of storage in the plant root zone. Particular soil profile conditions are required.

Surface Irrigation: A method by which the soil surface is used to convey the water to the point of infiltration into the soil. The following surface application methods are used: flooding from field ditches; border irrigation; checks; basins; furrows; and corrugations.

Tail Water Runoff: Irrigation water that runs off the surface of irrigated fields. Sometimes referred to as waste water or surface return flow.

Tangible Benefits: Those benefits, either primary or secondary, that can be expressed in monetary terms.

Tangible Damages: Those damages that can be evaluated in monetary terms.

Total Return Flow: All water that returns to a source of supply after having been diverted for any purpose.

Used Water: Any water that has been used by man for any purpose, including irrigation, municipal, industrial, power, recreation, fish, and wildlife.

Water Quality: The sum total of all those properties, characteristics, and attributes which determine the suitability of water for any desired beneficial use.

Water Renovation: Restoration or improvement of quality by reducing the amount of pollutants present. To restore to some former state of purity.

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